UNITED STATES PATENT AND TRADEMARK OFFICE

UNITED STATES DEPARTMENT OF COMMERCE
United States Patent and Trademark Office
Address: COMMISSIONER FOR PATENTS
P.O. Box 1450
Alexandria, Virginia 22313-1450
www.uspto.gov

APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
10/603,802	06/26/2003	Mats Leijon	66291-351	2804

7590 10/31/2003

John P. DeLuca
Watson Cole Grindle Watson, P.L.L.C.
Suite 1000
1400 K Street, N.W.
Washington, DC 20005-2477

EXAMINER	
MULLINS, BURTON S	

ART UNIT	PAPER NUMBER
2834	

DATE MAILED: 10/31/2003

Please find below and/or attached an Office communication concerning this application or proceeding.

RECEIVED
NOV - 6 2003
TECHNOLOGY CENTER 2800

Office Action Summary	Application No. 10/603,802	Applicant(s) LIEJON, MATS	
	Examiner Burton S. Mullins	**Art Unit** 2834	

-- Th MAILING DATE of this communication appears on th cover sheet with the correspondence address --

Period for Reply

A SHORTENED STATUTORY PERIOD FOR REPLY IS SET TO EXPIRE 3 MONTH(S) FROM THE MAILING DATE OF THIS COMMUNICATION.

- Extensions of time may be available under the provisions of 37 CFR 1.136(a). In no event, however, may a reply be timely filed after SIX (6) MONTHS from the mailing date of this communication.
- If the period for reply specified above is less than thirty (30) days, a reply within the statutory minimum of thirty (30) days will be considered timely.
- If NO period for reply is specified above, the maximum statutory period will apply and will expire SIX (6) MONTHS from the mailing date of this communication.
- Failure to reply within the set or extended period for reply will, by statute, cause the application to become ABANDONED (35 U.S.C. § 133).
- Any reply received by the Office later than three months after the mailing date of this communication, even if timely filed, may reduce any earned patent term adjustment. See 37 CFR 1.704(b).

Status

1)☒ Responsive to communication(s) filed on 26 June 2003.

2a)☐ This action is **FINAL**. 2b)☒ This action is non-final.

3)☐ Since this application is in condition for allowance except for formal matters, prosecution as to the merits is closed in accordance with the practice under *Ex parte Quayle*, 1935 C.D. 11, 453 O.G. 213.

Disposition of Claims

4)☒ Claim(s) 32-70 is/are pending in the application.

4a) Of the above claim(s) _____ is/are withdrawn from consideration.

5)☐ Claim(s) _____ is/are allowed.

6)☒ Claim(s) 32-70 is/are rejected.

7)☒ Claim(s) 32-70 is/are objected to.

8)☐ Claim(s) _____ are subject to restriction and/or election requirement.

Application Papers

9)☐ The specification is objected to by the Examiner.

10)☒ The drawing(s) filed on _____ is/are: a)☐ accepted or b)☐ objected to by the Examiner.

Applicant may not request that any objection to the drawing(s) be held in abeyance. See 37 CFR 1.85(a).

11)☐ The proposed drawing correction filed on _____ is: a)☐ approved b)☐ disapproved by the Examiner.

If approved, corrected drawings are required in reply to this Office action.

12)☐ The oath or declaration is objected to by the Examiner.

Priority under 35 U.S.C. §§ 119 and 120

13)☒ Acknowledgment is made of a claim for foreign priority under 35 U.S.C. § 119(a)-(d) or (f).

a)☐ All b)☐ Some * c)☐ None of:

1.☐ Certified copies of the priority documents have been received.

2.☒ Certified copies of the priority documents have been received in Application No. 08/973,019.

3.☐ Copies of the certified copies of the priority documents have been received in this National Stage application from the International Bureau (PCT Rule 17.2(a)).

* See the attached detailed Office action for a list of the certified copies not received.

14)☐ Acknowledgment is made of a claim for domestic priority under 35 U.S.C. § 119(e) (to a provisional application).

a) ☐ The translation of the foreign language provisional application has been received.

15)☐ Acknowledgment is made of a claim for domestic priority under 35 U.S.C. §§ 120 and/or 121.

Attachment(s)

1) ☒ Notice of References Cited (PTO-892)
2) ☐ Notice of Draftsperson's Patent Drawing Review (PTO-948)
3) ☐ Information Disclosure Statement(s) (PTO-1449) Paper No(s) _____.
4) ☐ Interview Summary (PTO-413) Paper No(s). _____.
5) ☐ Notice of Informal Patent Application (PTO-152)
6) ☐ Other: .

DETAILED ACTION

Drawings

1. The drawings are objected to under 37 CFR 1.83(a). The drawings must show every feature of the invention specified in the claims. Therefore, the "insulated/uninsulated" conductive elements (claim 39), the "discontinuously decreasing radius as the slot radius decreases" (claim 44), the "plurality of system voltage levels" (claim 56), the "plurality of separate tappings configured to connect to different system voltage levels" (claim 57), the "separate windings" (claim 58), "plurality of electrical systems of different voltages" (claim 59) must be shown or the feature(s) canceled from the claim(s). No new matter should be entered.

A proposed drawing correction or corrected drawings are required in reply to the Office action to avoid abandonment of the application. The objection to the drawings will not be held in abeyance.

Claim Objections

2. Claims 62-63 are objected to because of the following informalities: In claims 62 and 63, change "outer" to –outermost–.

Claim Rejections - 35 USC § 112

3. The following is a quotation of the first paragraph of 35 U.S.C. 112:

> The specification shall contain a written description of the invention, and of the manner and process of making and using it, in such full, clear, concise, and exact terms as to enable any person skilled in the art to which it pertains, or with which it is most nearly connected, to make and use the same and shall set forth the best mode contemplated by the inventor of carrying out his invention.

4. Claims 32-70 are rejected under 35 U.S.C. 112, first paragraph, as failing to comply with the written description requirement. The claim(s) contains subject matter which was not described in the specification in such a way as to reasonably convey to one skilled in the relevant art that the inventor(s), at the time the application was filed, had possession of the claimed invention. In claim 32, the recitation "a high-voltage stator winding configured to operate in an inclusive range of above 36 kV through a system voltage of a power network" constitutes new matter because it narrows the scope of the claimed high voltage machine to a range bounded by a lower limit of 36 kV. This lower limit is not synonymous with that defined by the original disclosure. The specification defines high voltage as "voltages exceeding 10 kV and up to the voltage levels which occur for power networks" (p.17, lines 11-13) and further states that "[t]he invention is generally applicable to rotating electrical machines for voltages exceeding 10 kV" (p.21, lines 7-8). Thus, the disclosed lower limit of applicant's high voltage machine is 10 kV, not 36 kV. There is nothing in the original disclosure which would prompt one of ordinary skill to choose 36 kV as the lower limit in the claimed range.

Applicant points out that support exists at p.5, line 34-p.6, line 6, p.6 lines 8-14, page 9 lines 12-21, and p.14 lines 29-32, and that the presently claimed range of "above 36kV through a system voltage of a power network" clearly lies within the above-noted disclosed range. While this range does lie within the originally disclosed range of "voltages exceeding 10 kV" as defined at p.21, lines 7-8, it also presents a subset or species which was not originally disclosed. The prior art described has different maximum voltage levels, e.g., 25-

30 kV (p.6, line 14), 20 kV (p.6, line 24), power network voltages (p.8, lines 13-15), or up to 36 kV (p.9, line 13). Even if applicant is correct in assuming that one of ordinary skill could infer support based on the prior art for a range limit, how would one of ordinary skill choose the specific range limit of 36 kV when the limits on the disclosed prior art cover the range of 20 kV through power network voltages?

Applicant cites Wertheim, 191 USPQ 90, (CCPA 1976) which found that specific suggestions of particular values of 36% and 50% along with an overall range of 25-60% were sufficient to support a subsequent claim with a range of 35-60% that was not literally set forth in the original specification. However, in Wertheim, specific examples were described in the specification. In applicant's specification, although specific ranges of the prior art are described, no specific ranges of applicant's invention are described except that of "voltages exceeding 10 kV." Thus, as far as defining a range for the term "high voltage" in the present case, one of ordinary skill in the art would be presented with the choice of either inferring a lower limit from a number of conflicting ranges disclosed in the prior art, or relying upon the clear disclosure in applicant's description that defines the range as being between 10 kV and power network voltages.

5. Claims 32-70 are rejected under 35 U.S.C. 112, second paragraph, as being indefinite for failing to particularly point out and distinctly claim the subject matter which applicant regards as the invention. In claims 32, 49, 55, 60 and 61, the statement "in an inclusive range of above 36 kV through a system voltage of a power network" is indefinite and contradictory because it is not clear whether 36 kV is included or excluded from the claimed range of "36 kV through a system voltage of a power network". The use of the term "inclusive" suggests

that 36 kV comprises and is included in the lower limit of the range, while use of the phrase "above 36 kV" suggests that the 36 kV value is excluded from the range.

6. Claims 58 and 68 are rejected under 35 U.S.C. 112, second paragraph, as being indefinite for failing to particularly point out and distinctly claim the subject matter which applicant regards as the invention. In claim 58, "each separate winding" is vague and indefinite. What defines a "separate" winding? Does this refer to each winding in each slot? Or to a winding wound in more than one slot? In claim 68, recitation "free of...field control" is vague and indefinite.

Claim Rejections - 35 USC § 103

7. The text of those sections of Title 35, U.S. Code not included in this action can be found in a prior Office action.

8. Claims 32-37, 40-41, 45-46, 49-50, 52-53, 55, 59-64 and 66-70 are rejected under 35 U.S.C. 103(a) as being unpatentable over Laffoon (US 1,891,716) in view of Elton (US 4,853,565). Laffoon teaches a high voltage rotating electric machine comprising: a stator winding which is insulated to allow for high voltage operation (e.g., 33,000 or 66,000 volts) and direct connection of the machine to the network, i.e., "in an inclusive range of above 36 kv through a system voltage of a power network" (p.1, lines 39-50).

Laffoon does not teach that the high-voltage winding is: 1) flexible, and 2) comprises a current-carrying conductor, an inner layer having semi-conducting properties surrounding and being in electrical contact with said current-carrying conductor, a solid insulating layer

surrounding and contacting the inner layer, and an outer layer having semi-conducting properties surrounding and contacting the solid insulating layer.

Elton teaches a high-voltage, electrical cable 100 (Fig.7) comprising current-carrying conductors 102; an inner, semi-conducting "grading" layer 104 made of pyrolized glass fibers (c.7, lines 19-20) surrounding and being in electrical contact with the current-carrying conductor 102; a solid insulation layer 106 surrounding and contacting the inner layer; and an outer layer 110 having semi-conducting properties surrounding and contacting the solid insulating layer 106, as well as being in contact with ground, to thus bleed off static charge and thus prohibiting development of corona discharge (c.7, lines 23-28; lines 64-68).

Regarding the issue of cable "flexibility", Elton's windings 50 "initially extend axially and then bend circumferentially so as to provide a connection between one bar and a second circumferentially disposed bar in the stator core" (c.5, line 67-c.6, line 4). The manner of bending is shown in Fig.5. Thus, adequate "flexibility" is provided by such a bend. Also, Elton's teaching at c.8, lines 3-9 that "the semi-conducting layer is a glass fiber which can be chopped, mixed with resin and molded, or blown on any complex shaped substrate [so that] the layer can be placed in intimate contact with substantially all of the exterior surface of the insulator or housing..." suggests that the semi-conducting layer can be "molded" or "blown" onto a cable without causing cable rigidity. Finally, Elton refers to US 4,510,077 (Elton '077), incorporated by reference therein, for a detailed description of the characteristics of the cable material. Elton '077 teaches that a lubricant may be used in the material "to impart lubrication to and between the individual glass fibers, and as such permits the threads and cloths manufactured from these fibers to be subjected to mechanical stresses as incurred by

bending, folding and twisting without breakage of the fibers" (c.4, lines 8-16). Thus, Elton '077 teaches how to make the semi-conductive material flexible.

It would have been obvious to one having ordinary skill to modify Laffoon's high voltage machine winding and provide a flexible, high voltage, electrical cable per Elton et al. with grounded inner and outer semi-conductors separated by an insulator since such a cable would have been desirable to prohibit development of corona discharge.

Regarding independent claim 49, Laffoon teaches direct connection of his high voltage generator at normal distribution voltages, i.e. "system voltages", such as 33,000 or 66,000 volts (p.1, lines 39-50). Note also stator core 2.

Regarding independent claim 55, note rotor 1 opposite the stator core 2.

Regarding independent claim 60, since Laffoon and Elton teach applicant's apparatus, the method of making the apparatus including the steps of "configuring" and "threading" the cable is inherent.

Regarding independent claim 61, Elton's cable layers 104/106/110 (Fig.7) form an "electric field confining cover" surrounding the current-carrying conductor/s 102 and form a full, uninterrupted turn as seen in Fig.5.

Regarding claims 33-34, Elton's inner "grading" layer 104 has substantially a same potential as the conductor 102 since it "equalizes the electric charge about conductive strands 102" (c.7, lines 21-22); and outer layer 110 forms an equipotential surface surrounding the conductor. Regarding claims 35-36, a predetermined reference potential or "node", including ground, may be coupled to the semi-conducting layer (c.8, lines 13-21). Regarding claim 37,

since the semi-conductive layers have different levels of resistivity (c.8, lines 27-28), it can be inferred that separate potentials would be chosen for separate windings

Regarding claim 40, Elton's inner and outer layers 104/110 have respective inner and outer contact surfaces (not numbered, Fig.7) and are secured to the solid insulating layer 106 along substantially an entire length of each corresponding contact surface, since the cable extends axially within slots in the stator core.

Regarding claim 41, Laffoon's stator 2 is laminated (p.2, line 20).

Regarding claims 45 and 66, since Laffoon and Elton disclose a stator cable structure identical to applicant's claimed cable structure, the operation of Laffoon and Elton's cable "at 100% overload for a period of time from about 15 minutes to about two hours" would be inherent.

Regarding claim 46, Laffoon teaches "direct connection" to the distribution network at 33 or 66 kV levels. This "direct connection" would not require transformers.

Regarding claim 47, "means for controlling a magnetic field flow through the rotor" are inherent to any dynamo-electric machine and could include e.g., the inductance of the stator windings themselves.

Regarding claim 48, generators are operated on a network to compensate for inductive or capacitive loads.

Regarding claim 50, note the magnetic circuit formed by rotor 1 and stator core 2 in Laffoon, as well as the rotor (inherent) and stator of Elton's machine (Fig.5).

Regarding claim 52, since Laffoon and Elton disclose a stator cable structure identical to applicant's claimed cable structure, with the outer layer of Elton 110 in contact with the

stots, in operation the electric field of the machine outside the outer semi-conducting layer in the slots and in an end winding region would be near zero.

Regarding claim 53, the conductors in Laffoon and Elton are transposed (Laffoon, p.2, lines 31-32; Elton, Fig.6, c.6, lines 49-60).

Regarding claim 59, Laffoon's direct-connection would inherently provide "means for permitting exchange of electric energy between a plurality of electrical systems of different voltages", i.e., the machine operating at 33-66 kV, and the grid, which can operate at greater than 66 kV.

Regarding claim 62, the outermost layer 110 in Elton is in electrical contact with the stator (Fig.2).

Regarding claim 64, Elton's plurality of layers are substantially free of cavities and pores.

Regarding claims 67-70, Elton's cable is operable free of end winding loss since the semi-conducting layers provide equal potentials about the end regions of the windings (c.7, lines 6-7). Elton's cable is free of partial discharge and comprises multiple uninterrupted turns (Fig.5).

9. Claims 38 and 65 are rejected under 35 U.S.C. 103(a) as being unpatentable over Laffoon and Elton as applied to respective claims 32 and 61 above, and further in view of Elton et al. (US 4,622,116). Laffoon and Elton et al. do not teach semi-conducting layers having similar coefficients of thermal expansion.

Elton '116 teaches that it is well known to form different overlapping insulations with the same coefficient of thermal expansion in order to prevent thermal stress. Thermal stress separates and cracks the materials causing the insulation to fail (see c.7, lines 38-44).

It would have been obvious to one having ordinary skill to modify the winding of Laffoon and Elton such that the insulation and semi-conducting layers had similar or the same coefficients of thermal expansion per Elton '116 since such a modification would have been desirable to prevent failure of the windings caused by thermal aging and cycling.

10. Claim 42 is rejected under 35 U.S.C. 103(a) as being unpatentable over Laffoon and Elton as applied to claim 32 above, further in view of Shildneck (US 3,014,139). Laffoon and Elton do not teach that the stator has a plurality of radial slots having axial cylindrical openings.

Shildneck teaches a large, turbine generator (c.1, lines 13-14) comprising: a stator (core 14, Fig.3); a rotor (not shown, but part of turbine generator); and a high voltage, stator winding including a flexible, current-carrying conductor or cable 1 (Fig.1). The stator core includes plurality of radial slots (defined by slot openings 2a) having axial cylindrical openings 4 (Fig.1), said slots and cylindrical openings having a substantially circular cross section separated by narrower waist portions 5 between the cylindrical openings (Fig.1). The stator winding is wound through the holes in the slots (c.5, lines 56-59). This stator slot construction eliminates the need for slot wedges or other separate slot closing means to prevent the windings from coming out of the slots (c.2, lines 65-67).

It would have been obvious to modify Laffoon and Elton and provide a stator with radial slots and cylindrical openings per Shildneck since this would have been desirable to

eliminate the need for slot wedges or other separate slot closing means to prevent the windings from coming out of the slots.

11. Claim 43 is rejected under 35 U.S.C. § 103(a) as being unpatentable over Laffoon, Elton and Shildneck as applied to claim 42 above, further in view of GB 468,827. Laffoon, Elton and Shildneck disclose the claimed invention as claimed except for the cylindrical openings having a continuously decreasing radius as the slot radius decreases.

GB 468,827 discloses a stator for a machine with slots in the core having cylindrical openings. The radius of the openings decreases as the slot radius decreases. This allows the slots to be closely spaced around the circumference of the core and allows for increasing insulation thickness for the conductors in a radially outward direction. This accommodates the different potentials experienced by the conductors in the machine.

It would have been obvious to one of ordinary skill in the art at the time of the invention to have formed the slots of Laffoon, Elton and Shildneck such that it had a profile of alternating wide and narrow elements, like that shown by GB 468,827, so that the stator core itself provides radial separation of the windings without the need for additional elements. Moreover, this arrangement would allow thicker insulation of the outer conductors to accommodate higher potentials experienced by the outer windings.

12. Claims 32-37, 40-42, 45-46, 49-50, 52-53, 55, 59-64 and 66-70 are rejected under 35 U.S.C. 103(a) as being unpatentable over Shildneck (US 3,014,139) in view of Elton (US 4,853,565) and Parsons et al. in "Direct Generation of Alternating Current at High Voltages" (Journal IEEE, Sept.1929). Shildneck teaches a large, turbine generator (c.1, lines 13-14), i.e. "high voltage" machine, comprising: a stator (core 14, Fig.3); a rotor (not shown, but part of

turbine generator); and a high voltage, stator winding including a flexible, current-carrying conductor or cable 1 (Fig.1). However, Shildneck's conductor/cable does not comprise inner- and outer-semiconducting layers and an insulation therebetween. Neither is there specific mention of operation of the cable in the range of 36 kV to system voltage.

Elton et al. teaches a high-voltage, electrical cable comprising current-carrying conductors 102 (Fig.7); an inner, semi-conducting "grading" layer 104 made of pyrolized glass fibers (c.7, lines 19-20) surrounding and being in electrical contact with the current-carrying conductor 102; a solid insulation layer 106 surrounding and contacting the inner layer; and an outer layer 110 having semi-conducting properties surrounding and contacting the solid insulating layer 106, as well as being in contact with ground, to thus bleed off static charge and thus prohibiting development of corona discharge (c.7, lines 23-28; lines 64-68). In another form, a predetermined reference potential may be coupled to the semi-conducting layer (c.8, lines 13-21).

It would have been obvious to one having ordinary skill to modify Shildneck's high voltage machine winding and provide a high voltage, electrical cable per Elton et al. with grounded inner and outer semi-conductors separated by an insulator since such a cable would have been desirable to prohibit development of corona discharge.

Regarding the 36 kV-to-system-voltage operating range limitation, while neither Shildneck nor Elton teach specific operating ranges, the cable taught by their combined disclosures would have been capable of use at such voltages. If the prior art structure is capable of performing the intended use, i.e. "configured to operate in an inclusive range of above 36 kV through a system voltage", then it meets the claim.

As support for this assertion, the examiner directs attention to Parsons et al., "Direct Generation of Alternating Current at High Voltages" (Sept.1929). Parsons provides a general background of high voltage generators, including discussion of the advantages of direct-connection of high voltage generators to the grid, without the use of transformers (p.1065 and Section 3), and the financial savings to be gained thereby (Section 4, p.1068-1071). While Parsons is specifically directed to a 33 kV machine, he teaches that high voltage generation "has been increased due to the difficulties which arise with the heavy currents" and "...that if they [the authors] can show sound reasons for generating at a higher voltage, then 66 kV, a voltage recognized as one of the standard transmission voltages, would be the most advantageous" (p.1068). In the design of his generator (Section 6, p.1071), Parsons teaches that with regard to the cable structure and insulation in such high voltage machines, "[a]fter considering different schemes...it occurred to the authors that a concentric type of core conductor, of which knowledge was already available through its application in other directions, might be adopted. By incorporating this type of conductor it became possible to prepare designs with greatly increased phase voltage without increasing the voltage gradient across the winding insulation." The cross-sectional structure of Parson's concentric cable is shown in Fig.3. This concentric design "appears to afford a simple solution of the problem [i.e., of increased voltage gradient]. By its use an alternator can be so wound as to distribute the dielectric stress and to lower its mean value at that part of the machine where there is limited area, and the maximum of heat generation at the regions adjacent to the stator bore. In the designs of alternators for voltages of 33 kV and 44 kV between phases, there is sufficient

margin to permit insulated conductor bars to be used with thicknesses of insulation not exceeding those of which experience has proved satisfactory" (p.1071).

This basic concentric design is incorporated by Elton in his cable 100 (Fig.7), where the internal and external semi-conductive layers 104/110 are concentrically arranged around the conductor strands 102 to equalize the electric charge thereabout and around the exterior of the cable (c.7, lines 12-17). Thus, while not explicitly stated by Elton, operation of the cable at voltages greater than 36 kV is contemplated since a recitation of the intended use of the claimed invention must result in a structural difference between the claimed invention and the prior art in order to patentably distinguish the claimed invention from the prior art. If the prior art structure is capable of performing the intended use---as Shildneck and Elton's concentric cable is---then it meets the claim. In a claim drawn to a process of making, the intended use must result in a manipulative difference as compared to the prior art. See *In re Casey*, 152 USPQ 235 (CCPA 1967) and *In re Otto*, 136 USPQ 458, 459 (CCPA 1963).

13. Claims 38 and 65 are rejected under 35 U.S.C. 103(a) as being unpatentable over Shildneck, Elton and Parsons, as applied to respective claims 32 and 61 above, and further in view of Elton et al. (US 4,622,116). Shildneck, Elton and Parsons do not teach semi-conducting layers having similar coefficients of thermal expansion.

Elton et al. (US '116) teach that it is well known to form different overlapping insulations with the same coefficient of thermal expansion in order to prevent thermal stress. Thermal stress separates and cracks the materials causing the insulation to fail (see c.7, lines 38-44).

It would have been obvious to one having ordinary skill to modify the winding of Shildneck, Elton and Parsons such that the insulation and semi-conducting layers had similar or the same coefficients of thermal expansion per Elton et al. (US '116) since such a modification would have been desirable to prevent failure of the windings caused by thermal aging and cycling.

14. Claim 43 is rejected under 35 U.S.C. § 103(a) as being unpatentable over Shildneck, Elton and Parsons, further in view of GB 468,827. Shildneck, Elton and Parsons disclose the claimed invention as claimed except for the cylindrical openings having a decreasing radius as the slot radius decreases.

GB 468,827 discloses a stator for a machine with slots in the core having cylindrical openings. The radius of the openings decreases as the slot radius decreases. This allows the slots to be closely spaced around the circumference of the core and allows for increasing insulation thickness for the conductors in a radially outward direction. This accommodates the different potentials experienced by the conductors in the machine.

It would have been obvious to one of ordinary skill in the art at the time of the invention to have formed the slots of Shildneck, Elton and Parsons such that it had a profile of alternating wide and narrow elements, like that shown by GB 468,827, so that the stator core itself provides radial separation of the windings without the need for additional elements. Moreover, this arrangement would allow thicker insulation of the outer conductors to accommodate higher potentials experienced by the outer windings.

Allowable Subject Matter

15. Claims 39, 44, 51, 54 and 56-58 would be allowable if rewritten to overcome the objections and rejection(s) under 35 U.S.C. 112, first and second paragraphs, set forth in this Office action and to include all of the limitations of the base claim and any intervening claims.

Regarding claim 39, the prior art does not fairly teach or suggest that the cable conductor comprises a plurality of conductive elements, selected ones of said plurality of conductive elements being insulated from each other, and selected other ones of said plurality of conductive elements being uninsulated in order to effect contact with the inner layer. There is no teaching or suggestion in Laffoon, Elton and Shildneck to combine insulated and uninsulated conductor elements so that some uninsulated conductors contact the inner layer. Laurell teaches plural conductors (Fig.2), but each is insulated by insulation 2. There is no teaching or suggestion that some conductors are insulated, and some are not insulated.

Regarding claim 44, GB 468,827 teaches continuously decreasing radius of the cylindrical openings and slot radius decreases. There are no discontinuities in radius relative to slot radius.

Regarding claim 51, neither Laffoon, Elton, Shildneck nor Parsons teach that their cable's outer semi-conducting layer is severed at a plurality of locations forming a plurality of parts separately connectable to earth potential.

Regarding claim 54, as with claim 39 above, there is no teaching in Laffoon, Elton, Shildneck, Parsons or Laurell that the conductive elements of the current-carrying conductor comprise at least one of non-insulated and insulated wires, stranded into a plurality of layers.

Regarding claim 56, Laffoon teaches different system level voltages such as 33 and 66 kV, but does not teach that his machine may be "selectively connectable" to such a plurality of

system level voltages. Rather, it appears Laffoon teaches only one system level voltage. The remaining prior art does not teach plural system level voltages or selective connection of the machine cable thereto.

Similarly, with regard to claims 57-58, Laffoon nor the prior art teaches plural separate tappings for the windings to connect to different system voltage levels, or that each "separate winding" [sic] connects to the system voltage level.

Response to Arguments

16. Applicant's arguments with respect to claims 32-70 have been considered but are moot in view of the new ground(s) of rejection.

Conclusion

17. The prior art made of record and not relied upon is considered pertinent to applicant's disclosure.

18. Any inquiry concerning this communication or earlier communications from the examiner should be directed to Burton S. Mullins whose telephone number is 305-7063. The examiner can normally be reached on Monday-Friday, 9 am to 5 pm. If attempts to reach the examiner by telephone are unsuccessful, the examiner's supervisor, Nestor Ramirez can be reached on 308-1371. The fax phone number for the organization where this application or proceeding is assigned is (703) 872-9306.

Any inquiry of a general nature or relating to the status of this application or proceeding should be directed to the receptionist whose telephone number is 308-0956.

Burton S. Mullins
Primary Examiner
Art Unit 2834

bsm
9 October 2003

Notice of References Cited	Application/Control No. 10/603,802	Applicant(s)/Patent Under Reexamination LIEJON, MATS	
	Examiner Burton S. Mullins	Art Unit 2834	Page 1 of 2

U.S. PATENT DOCUMENTS

*		Document Number Country Code-Number-Kind Code	Date MM-YYYY	Name	Classification
	A	US-1,891,716	12-1932	Laffoon	310/196
	B	US-			
	C	US-			
	D	US-			
	E	US-			
	F	US-			
	G	US-			
	H	US-			
	I	US-			
	J	US-			
	K	US-			
	L	US-			
	M	US-			

FOREIGN PATENT DOCUMENTS

*		Document Number Country Code-Number-Kind Code	Date MM-YYYY	Country	Name	Classification
	N					
	O					
	P					
	Q					
	R					
	S					
	T					

NON-PATENT DOCUMENTS

*		Include as applicable: Author, Title Date, Publisher, Edition or Volume, Pertinent Pages)
	U	Parsons et al., "Direct Generation of Alternating Currents at High Voltages", Journal IEEE, V67 n393, Sept.1929.
	V	Rosen, "Generation at 33 kV Proved by Performance", Electrical World, May 6, 1933.
	W	Parsons, "Corona Discharge on Alternators", Electrical Times, 4 April 1935.
	X	"Development of High Voltage Generators", Electrical Times, v83, n2153, 26 Jan 1933.

*A copy of this reference is not being furnished with this Office action. (See MPEP § 707.05(a).)
Dates in MM-YYYY format are publication dates. Classifications may be US or foreign.

Notice of References Cited	Application/Control No. 10/603,802	Applicant(s)/Patent Under Reexamination LIEJON, MATS	
	Examiner Burton S. Mullins	Art Unit 2834	Page 2 of 2

U.S. PATENT DOCUMENTS

*		Document Number Country Code-Number-Kind Code	Date MM-YYYY	Name	Classification
	A	US-			
	B	US-			
	C	US-			
	D	US-			
	E	US-			
	F	US-			
	G	US-			
	H	US-			
	I	US-			
	J	US-			
	K	US-			
	L	US-			
	M	US-			

FOREIGN PATENT DOCUMENTS

*		Document Number Country Code-Number-Kind Code	Date MM-YYYY	Country	Name	Classification
	N					
	O					
	P					
	Q					
	R					
	S					
	T					

NON-PATENT DOCUMENTS

*		Include as applicable: Author, Title Date, Publisher, Edition or Volume, Pertinent Pages)
	U	Friedlaender, "Travelling Waves in High Voltage Alternator Windings", Journal of the Institution of Electrical Engineers, v89, pt. (Power Eng) n 11, Oct 1942, p.492-508.
	V	Horsley, "Operating Experience with High-Voltage Alternators", Journal of the Institution of Electrical Engineers, v87 no.528, Dec 1940, p.679-686.
	W	
	X	

*A copy of this reference is not being furnished with this Office action. (See MPEP § 707.05(a).)
Dates in MM-YYYY format are publication dates. Classifications may be US or foreign.

DIRECT GENERATION OF ALTERNATING CURRENT AT HIGH VOLTAGES.

By the Hon. Sir CHARLES A. PARSONS, O.M., K.C.B., F.R.S., Honorary Member, and J. ROSEN, Member.

(Paper received 15th January, 1929; read before THE INSTITUTION *21st March, before the* NORTH-EASTERN CENTRE *25th March, before the* NORTH-WESTERN CENTRE *9th April, and before the* SOUTH MIDLAND CENTRE *15th April,* 1929.)

SUMMARY.

The authors begin by pointing out, with the help of a mechanical analogy, the true place which the alternating-current transformer takes in the group of plant considered to-day to be standard for the generation, transmission and distribution of electric power on a large scale.

They propose the use of high-voltage alternators and the partial abolition of transformers. In support of these proposals, the authors discuss the gradual growth of conditions favourable to the ~~introduction of the~~ high-voltage alternator, and describe the obstacles in the way of further development at lower voltages.

This discussion leads naturally to the advantages to modern alternator design to be derived from the acceptance of the principle of direct generation at high voltages.

Apart from the design of the alternator itself, including its cable leads, there are many ways in which the adoption of such an alternator would effect financial economy in capital outlay and running expenses, and these matters the authors proceed to set out.

They then take a brief survey of what has already been done in the past in the field of direct generation at 30 000 volts, and describe in detail a 33 000-volt, 25 000-kW, 3 000-r.p.m. alternator of unique design, built for the North Metropolitan Electric Power Supply Co., for installation in the new power station at Brimsdown, North London. The operating experiences on site since the setting to work of the alternator in August 1928 are stated.

As a matter of interest to those engineers and designers engaged in alternator construction and development, an outline is given of some of the experimental research carried out by the authors in the working out of the practical details of the new design, and of the tests made at works on the completed alternator.

The paper concludes with some reference to the future possibilities of the extended use of direct generation at high voltages, and the authors ask for a candid expression of opinion from their critics.

TABLE OF CONTENTS.

(1) PRELIMINARY CONSIDERATIONS OF THE FUNCTION OF THE TRANSFORMER.

Engineering history contains several examples of a complete change of procedure brought about by developments in a given field of work.

An example in the field of mechanical engineering is the use of step-up gearing in the early days of marine propulsion by screw propellers—a practice which is to-day reversed, for modern marine steam turbines and some of the latest marine Diesel engines are now connected to their propeller shafts through speed-reduction gears. Since an intermediate period in the development of the triple-expansion engine no gearing has been used.

Just as the mechanical gear forms a link between the prime mover and the driven machine, so in the field of electric power generation and utilization by high-tension alternating currents the transformer has for many years been a necessary link between generator and network, and between network and driven apparatus.

Transformers were first introduced about the year 1885 in the early days of electric power generation, and were used for stepping down from a comparatively high generator and transmission voltage to a low voltage suitable for arc lamps and other current-consuming apparatus.

About 1890 the transmission voltage, using underground cables, had been raised to 10 000 by Ferranti and Partridge, by whom much pioneer work was done; and alternators of the same voltage were installed in the Deptford power station. These alternators were of low-speed design and had revolving armatures, in spite of the high generating voltage. They were probably unique in this respect.

The transmission voltage was transformed down in two steps—10 000/2 500, and then 2 500/100. Here we have the complete antithesis of present practice, where generation at 6 600 volts or 11 000 volts is usual, these voltages being stepped up to 22 kV or 33 kV for the distribution network immediately surrounding the power station, and possibly again stepped up to 66 kV or 132 kV for the grid system of intercommunication of power networks.

In view of these considerations, there is ample precedent for a reversal or change of procedure, if such change is in the interests of modern development. The use of high-voltage alternators is, in fact, proposed by the authors, and with it the abolition of step-up transformers for some part of the power to be distributed.

(2) The Growth of Conditions Favourable to the Introduction of the High-Voltage Alternator.

Apart from the work of Ferranti, pioneer development in England and America at voltages above 6 000 was not encouraged by the engineers responsible for design and operation of power plants.

In America, in 1899, the 5 000-h.p. water turbo-alternators at Niagara were built to generate 2-phase current at 5 000 volts. The transmission voltage was 11 000 volts. The alternators had an outer revolving field with a central stationary armature, and were widely known as the "umbrella" type.

In England, the early steam-turbine-driven alternators were designed with a revolving armature, which usually consisted of a smooth core having the windings laid over it and secured by binding wire. This type with a smooth core was used up to 2 000 volts, and up to 4 000 volts with a tunnel winding. They were single-phase machines.

It was found that at the higher voltages, especially where there was more than one phase, the difficulties in manufacture and insulation were great, and the revolving armature was discarded in favour of the revolving field.

Turbo-type revolving-field alternators of 1 500 kW at 1 500 r.p.m., generating at 11 000 volts, were built in 1905, and are still in operation.

While mica insulation was fitted to the end-windings, no mica was used in the conductor-insulating tubes, which were made of varnished fibrous materials.

Many alternators were built subsequently with improved constructional details, at voltages up to 13 000 volts. It was not until 1921 that the authors' attention was again drawn to the possibilities of high-voltage generators, at a discussion in Newcastle-on-Tyne with an engineer who was responsible for a power supply system where the greater part of the energy was transmitted in bulk at 22 kV to a point some distance from the power station, the generating pressure being 11 000 volts. He expressed a wish that a reliable generator might be designed capable of generating direct at the higher voltage. This change of attitude on the part of a supply engineer led the authors to believe that the problem might be a general one; it came at a time when the authors' thoughts were turning to the design of the largest units, which have now materialized—that is, 50 000- and 100 000-kW units.

With the increase in size of generating unit, the greater were the advantages to be gained in the design of alternators by direct generation at 22 kV or 33 kV, and as there were also advantages to be gained in the power station it was felt desirable to make investigations.

Table 1.

Comparison of Stator Conductors for 1 500-r.p.m., 50-cycle Alternators.

Voltage		6 600	11 000	13 400	18 000	22 000	33 000
50 000 kW at 0·8 power factor	Current, in amperes	5 470	3 280	2 700	2 010	1 640	1 095
	Total number of conductors	48	84	96	126	162	240
	Conductors per pole per phase	4	7	8	10½	13½	20
	Number of parallel circuits	4 (2 slots in parallel)	2	2	1	1	1
75 000 kW at 0·8 power factor	Current, in amperes	8 200	4 920	4 040	3 010	2 460	1 640
	Total number of conductors	30	48	60	84	96	144
	Conductors per pole per phase	2½	4	5	7	8	12
	Number of parallel circuits	8 (4 slots in parallel)	4 (2 slots in parallel)	2 (2 slots in parallel)	2	2	1
100 000 kW at 0·8 power factor	Current, in amperes	10 950	6 560	5 400	4 020	3 280	2 190
	Total number of conductors	24	42	48	60	84	120
	Conductors per pole per phase	2	3½	4	5	7	10
	Number of parallel circuits	8 (4 slots in parallel)	4 (2 slots in parallel)	4 (2 slots in parallel)	2 (2 slots in parallel)	2	1

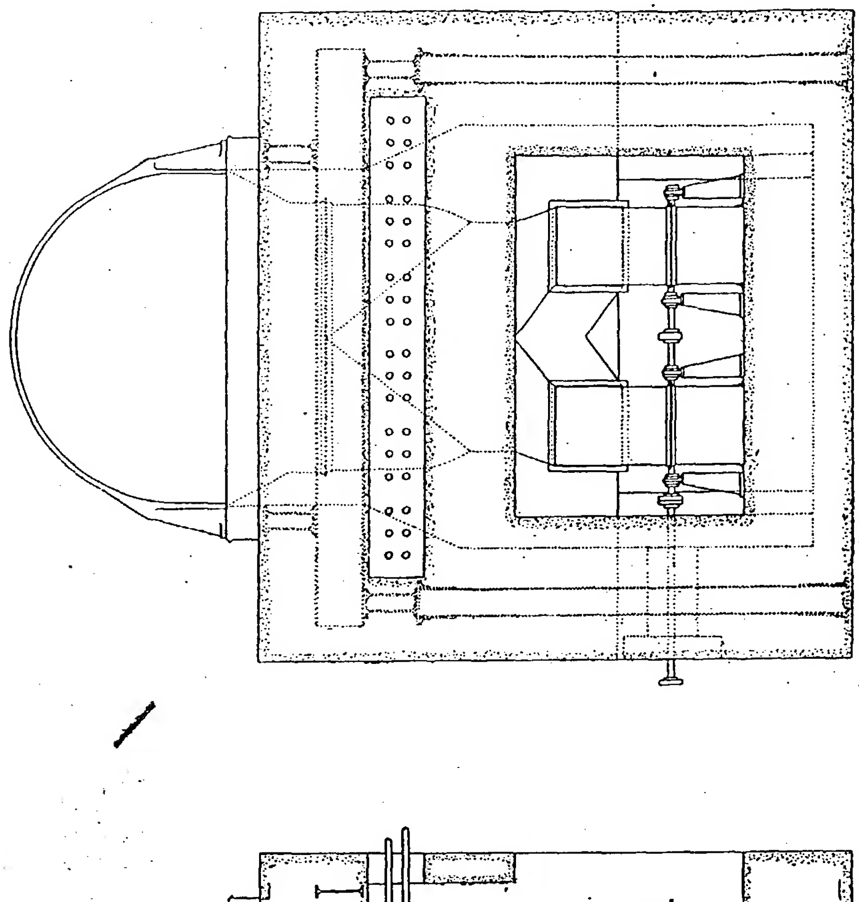


FIG. 1.—11 000-volt, 94 000-kVA alternator. Arrangement of leads through foundation block

In order to illustrate the difficulties in the design of the largest units, and the lack of flexibility at lower voltages, a list (Table 1) of the current values and approximate number of conductors corresponding to various voltages is given for alternators of 50 000, 75 000 and 100 000 kW capacity.

It is clear that for large units at the lower voltages, to keep the current per conductor low, conductors in two or more adjacent slots would be connected in parallel, thus presenting difficulties in winding, in order that the resultant voltages of each parallel path should be equal in magnitude and also in phase.

The number of conductors in series per phase, upon which the designer can ring the changes, may be as low as 10 or 12. This restriction may impose such limits on the design that an alternator to meet the specified conditions may differ by as much as 20 per cent from the most favourable proportions, with consequent lowering of efficiency.

(3) The Advantages of High-Voltage Generation in the Design of the Large Alternator.

On investigation, it was found that in many lay-outs the cost of the leads for a high-voltage machine would be much less and that the cost of the copper busbars and switchgear would also be lower. In fact, in the largest units, one switch only would be employed to carry and break the currents when, at lower voltages, two would be necessary.

Considering the cable ducts for an alternator of 94 000 kVA, 11 000 volts, 4 920 amperes, and assuming a density of 820 amperes per sq. in. with lead-covered, paper-insulated, single cables, six cables, each 1 sq. in. area, would be required for each phase. Assuming that cables are run from the stator earth leads, then there would be a total of 36 cables to be led away from the machine. To suit the requirements of most electrical undertakings, the working density would be lower than that assumed, giving a still greater number of cables.

As it is impracticable to bring the leads through the end shields, the winding must be so arranged that the leads are led through the foundation block.

It is inadvisable to weaken the foundation block by bringing the leads through the sides, since the latter form the piers supporting the machine.

The leads cannot conveniently be taken down vertically on account of the ventilation system, and in practice it is found that the best arrangement is to form a cable tunnel in the concrete, running longitudinally from the machine terminals to the exciter end of the block. It will be appreciated that the tunnel has to be of sufficient size for accessibility in fitting the various parts in position.

For the 94 000-kVA, 11 000-volt alternator, much space is required to accommodate the cables and sealing ends mounted below the alternator terminals. Fig. 1 shows the arrangement for this machine. It is seen that the tunnel has to be made nearly the full width of the foundation block, and difficulty is experienced with the girders which reinforce the concrete.

With so many cables grouped together, the maximum output would not be obtained from them.

Most of these difficulties are overcome when an alternator of higher voltage is employed. Considering a pressure of 33 kV, the current is reduced from 4 920 amperes to 1 640 amperes; it will be seen at once that against 6 or 7 cables for the lower voltage machine there are only 2 cables per phase, and these can be loaded up to their full capacity.

A typical arrangement of the leads for the high-voltage machine is shown in Fig. 2. The leads and sealing ends are readily accommodated in the foundation block, the width of the tunnel being reduced from 14 ft. to 8 ft. 6 in., and the machine placed on a firmer foundation. The sizes of 33-kV cable-sealing bells are only slightly larger than those for 11 000 volts, and little extra space is therefore required for them.

Regarding the cost of cables, those for the 33-kV machine cost £20 per yard run, and for the 11 000-volt machine £37 per yard run for the above output.

As an example of the necessity for reducing the current in large units, the General Electric Co. of Schenectady, in designing the 208 000-kW unit for the State Line station of the State Line Generating Co., near Hammond, Ind., found it necessary to increase the alternator voltage for this purpose. There are three main units running at 1 800 r.p.m., comprising a high-pressure turbine driving a 76 000-kW alternator (0·85 power factor), and two low-pressure turbines, each driving a 62 000-kW alternator.

The main alternators were first designed for a voltage of 18 kV instead of the standard voltage of 13 400 volts. It was later found necessary to raise the voltage to 22 kV.*

The transmission voltages are 33, 66 and 132 kV; it is apparent that the generating voltage has been increased due to the difficulties which arise with the heavy currents.

The authors have been repeatedly reminded that if they can show sound reasons for generating at a higher voltage, then 66 kV, a voltage recognized as one of the standard transmission voltages, would be the most advantageous.

While 66 kV is a generator voltage which may be reached in course of development, it must be recalled that there are many conditions under which 22 kV and 33 kV would be considered economical, more especially where the power station is at the centre of, or at only a few miles' distance from, the main consumption of the power, and where underground cables may be employed for transmission. Several such plants may be quoted where the conditions for generating at 33 kV might be considered favourable, for example, Barton, Clyde Valley, the proposed site at Carrington, and others. All have surrounding areas which can economically consume power at 33 kV, and enable a saving to be made by direct generation and switching at 33 kV.

(4) Financial Savings Effected by Direct Generation at High Voltages.

The authors have worked out the savings which may be obtained with the use of such high-voltage alternators.

Where the generator can be constructed to supply the transmission system directly, without the intervention of step-up transformers, the whole sum, representing the cost of the transformers and their housing, and the

* *General Electric Review*, 1928, vol. 31, p. 7, and 1927, vol. 30, p. 5.

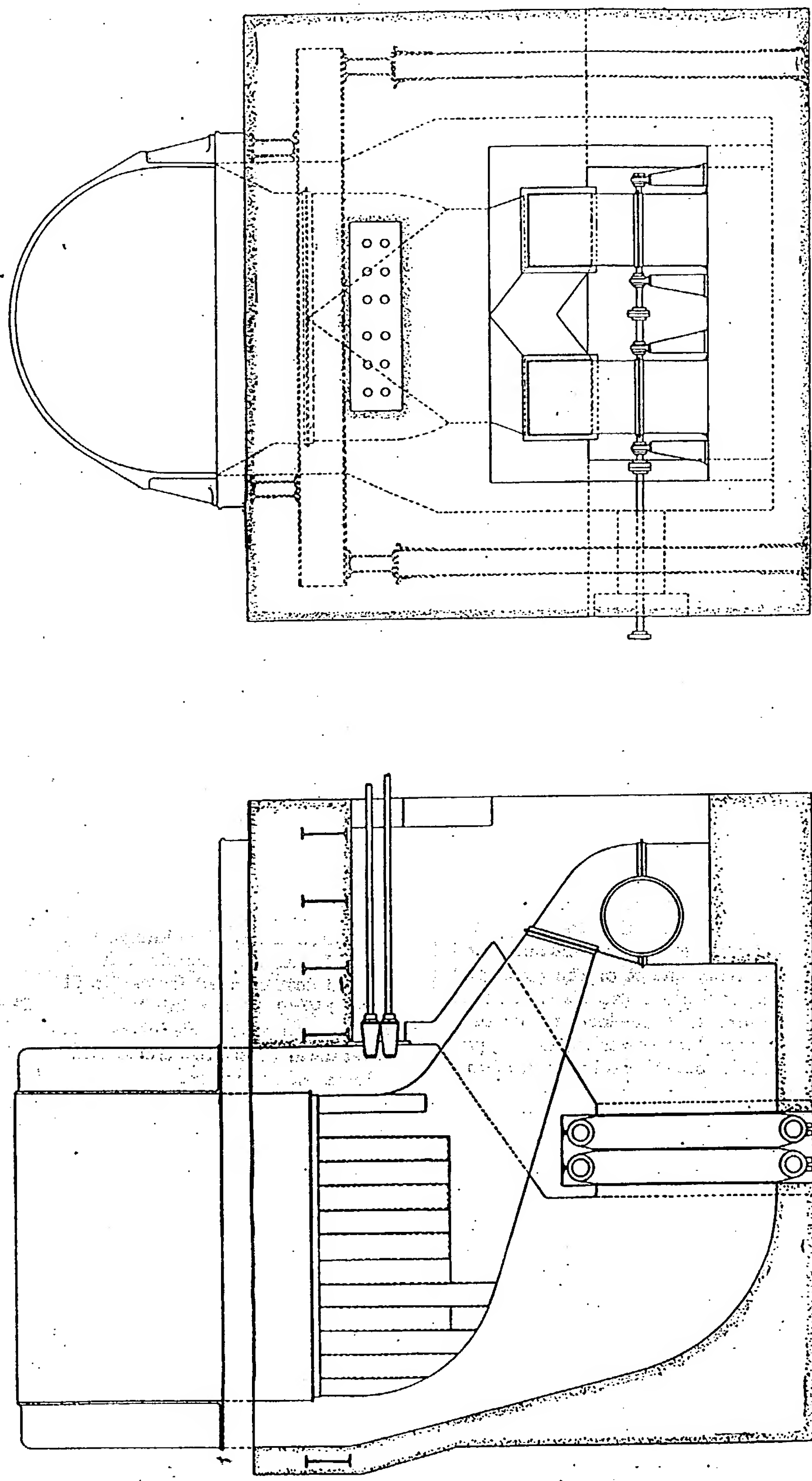


FIG. 2.—33 000-volt, 94 000-kVA alternator. Arrangement of leads through foundation block.

capitalized value of their losses, less the additional cost of the high-voltage generator, can be saved.

Where the generator voltage is stepped up at once to the transmission voltage, there is the advantage to power station designers of freedom of choice in placing the switchgear either on the l.t. or h.t. sides of the transformers.

The various items in which there is a direct financial saving by the use of high-voltage generators may be summarized under the following headings:—

(*a*) Cables.
(*b*) Transformers.
(*c*) Transformer losses.
(*d*) Transformer cooling equipment.
(*e*) Buildings.
(*f*) Switchgear.

(*a*) *Cables.*—As already stated, the cost of the cables between generators and switchgear or transformers increases rapidly with the current and size of unit. The expense of laying the heavy cables will also naturally be greater.

(*b*) *Transformers.*—These will usually be 3-phase units up to 20 000 or 30 000 kVA, and banks of three single-phase units for larger outputs. Artificial cooling, either by water or air, will be required above 15 000 kVA and is included in the prices given below. The figures apply to transformers stepping up the generator voltage to 33 kV.

(*c*) *Transformer losses.*—The capitalized value of transformer losses represents a considerable part of the total capital outlay, and is so much greater than the extra cost of the high-tension generator that the saving of this expenditure is alone sufficient to justify the use of higher generating voltages, when transformers can be eliminated. The correct basis on which to charge the transformer losses is not always easy to determine, and depends on the size and arrangement of the plant and system and the operating conditions, especially the load factor. It may be assumed that the load factor of a large generating unit in a modern power station supplying an extensive network is somewhere between 50 and 70 per cent.

The annual cost of the losses can be obtained by reckoning the actual generating cost of the losses thus obtained, to which must be added a fixed charge per kW of maximum demand, representing the proportion of the fixed charges of the installation which is chargeable at the point at which the transformers are situated; for step-up transformers at the generating station this charge should be lower than for distant distribution transformers, where the losses are supplied through the transmission system.

In order to capitalize the annual cost of the transformer losses, a rate of about 10 per cent per annum may be taken, to include interest on capital, depreciation, obsolescence and insurance.

(*d*) *Transformer cooling equipment.*—The cost of running the transformer cooling-plant motors (oil pump and fan) must be added to the cost of fixed losses of the transformer, as the cooler is usually in service all the time the transformer is alive. Where water-cooling is used the cost of water must be considered, although it is only in exceptional cases that this charge is appreciable.

(*e*) *Buildings.*—Transformer banks are now usually installed out-of-doors, but a certain expenditure is incurred for foundations and accessory structures. There may also be some saving in the construction of cable ducts and switchgear housing.

(*f*) *Switchgear.*—The cost of switchgear increases rapidly when the current exceeds certain values, and may become excessively high for very large units at low voltage. The cost of maintenance, also, will be higher for the very heavy gear required for large currents.

As a representative plant, a unit of 75 000 kW will be taken, giving its full output at a power factor of 0·8, the equivalent output thus being 94 000 kVA. It will be assumed that a generator of this output is wound for 11 000 or 33 000 volts, and has to supply a network at 33 000 volts, so that a transformer bank will be necessary in the first case. It is assumed that the switchgear is on the 33-kV side. The following comparison can then be made:—

	"A"	"B"
Generator output, kVA	94 000	94 000
Generator voltage	11 000	33 000
Approximate additional cost of generator	—	£10 000
Cost of cables (100 yards' run)	£3 675	£2 000
Cost of transformers	£19 000	—
Transformer losses.		
Fixed losses, kW	250	—
Variable loss at full load, kW	400	—
Variable loss at 60 per cent load factor, kW	144	—
Transformer cooling equipment.		
Input to motors, kW	50	—
Reduction in cost of buildings, etc., and transformer foundations	—	£500
Annual cost of fixed losses [at £1 per kW (0·1d. per unit)]	£1 400	—
Annual cost of variable losses	£925	—
Capitalized cost of transformer losses at 10 per cent	£23 250	—

The 33-kV machine thus shows a capital saving of £44 425, from which the extra cost of the former must be deducted, leaving a net saving of £34 400.

Where the generator voltage is stepped up to 66 kV it might be possible to take advantage of the low step-up ratio and effect a saving by the use of auto-transformers.

	"A"	"B"
Generator voltage	11 000	33 000
Cost of cables (100 yards' run)	£3 675	£2 000
Cost of auto-transformers	£16 000	£9 750
Capitalized value of losses	£20 000	£12 500
Reduction in building costs	—	£1 000
Cost of switchgear	£9 000	£6 200

The total capital saving on the 33 000-volt generator is then £19 225, less £10 000, or a net saving of about £9 000.

The above figures are approximate, but are submitted

as representative of the conditions prevailing at the date when the paper was written.

(5) Historical Survey of Past Alternator Construction for Direct Generation at 30 kV.

The use of a generating pressure as high as 30 kV is not in itself new, since Prof. Mengarini installed two 5 200-kVA, 30-kV alternators running at 450 r.p.m. and generating 3-phase current at 45 cycles per sec. in the hydro-electric power station of the Societa Anglo Romana at Subiaco, on the upper reaches of the River Aniene. The power was transmitted to Rome, a distance of 34 miles.

The engineers of the Ganz Co., Ltd., constructed these 30-kV alternators in 1905, in addition to others for service in Italy.

Credit must be given to the engineers for this early pioneer work, and the success of these plants shows a thorough understanding of the art of insulation.

The machines have not been repeated in recent times. The amount of power transmitted over long distances from hydro-electric stations has very much increased, and the transmission pressures now employed in Italy have been increased to 100 kV and over. As it is unusual to have a large demand adjacent to a hydro-electric power station situated in the hills, the pressure of 30 kV has fallen into disuse, and the generating voltage was reduced to a lower figure suitable for the design of the moderately large electrical units employed.

The methods by which the engineers succeeded in constructing several successful 30-kV alternators as far back as 1905 are well worthy of study. The precautions which they recommended are now essential in electrically high-stressed materials such as are used in underground cables, etc.

From experience, it was found that the temperatures at which the alternators operated had to be kept at a moderate figure. Any difficulties that were experienced were traced to charring of the insulation. These difficulties emphasized the importance of using mica between turns, where the potentials were low, as well as between phases and to earth.

No attempt was made to grade the conductor insulation, but micanite was used throughout, and attempts were made thoroughly to impregnate the insulation and to expel the air.

The stator end-windings were not clamped, although the plants feeding the overhead transmission lines must have been subject to heavy short-circuits, surges, etc.

The necessary wide spacing of the end-windings, due to the high voltages, with large distances between phases and to earth, no doubt accounts for the remarkable freedom from mechanical failures or movement of the windings.

The authors take the opportunity of mentioning here this explanation of the lower mechanical stresses and forces in the end-windings, as a natural criticism has been levelled at a construction which removes the transformer, which, in the past, has acted as a buffer between the system and the alternator.

The forces on the end-windings are, in fact, much reduced, but this problem is dealt with later in the paper.

(6) The Design of the 33 000-Volt, 25 000-kW, 3 000-r.p.m. Alternator now Installed at Brimsdown Power Station, North London.

The authors' experience as far back as 1905 led them to believe that the voltage with ordinary design could be much increased, but not sufficiently to keep pace with modern developments in 1921. Some better and simpler solution had to be sought, and, in view of these considerations, the authors directed their attention to the design of a high-voltage winding for incorporation in the largest alternators. Several designs were prepared.

In all investigations their efforts were principally directed towards the use of recognized standard insulations, such as micanite, without subjecting the materials to greater electrical stresses or employing greater thicknesses than those which had already proved satisfactory over a period of years.

After considering different schemes, including the grading of the quality and thickness of the insulation, it occurred to the authors that a concentric type of core conductor, of which knowledge was already available through its application in other directions, might be adopted. By incorporating this type of conductor it became possible to prepare designs with greatly increased phase voltage without increasing the voltage gradient across the winding insulation.

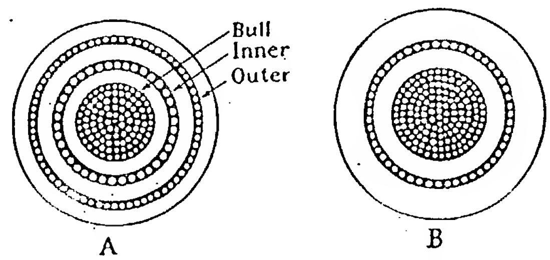


Fig. 3.—Sections through conductor bars.

The concentric conductor, which is the basis of the design and which is to be described, appears to afford a simple solution of the problem. By its use an alternator can be so wound as to distribute the dielectric stress and to lower its mean value at that part of the machine where there is limited area, and the maximum of heat generation at the regions adjacent to the stator bore. In the designs of alternators for voltages of 33 kV and 44 kV between phases, there is sufficient margin to permit insulated conductor bars to be used with thicknesses of insulation not exceeding those of which experience has proved satisfactory.

A section through one conductor bar is illustrated at "A" in Fig. 3 and resembles an ordinary concentric cable, with the exception that the insulation between conductors is of micanite.

There are three conductors per slot, nested one within the other, the conductors being wound in such a manner that the voltage is gradually stepped down from the innermost conductor. This formation of conductor is also very strong mechanically—a distinct advantage where the conductor projects beyond the stator core for coupling to the end-connections. For ease in description, the respective conductors in each slot are

referred to as the "bull," "inner" and "outer" (see Fig. 3).

The "bull" conductors of each phase are connected in series, and are then connected to the surrounding "inner" conductors which are again connected in series and finally connected to the "outer" conductors, which are starred to the ends of corresponding conductors of the remaining two phases, and then connected to earth. A diagram of connections is given in Fig. 4, in which the method of winding is clearly indicated.

Fig. 5 is a vector diagram from which, in the initial stages of design, the voltage difference between conductors in the same or different phases was readily obtained.

By numbering the conductors and using a straight-edge on the diagram, it is possible to trace the potentials at the different points round the whole of the windings.

The diagram of connections shown in Fig. 4 is for a 3-phase, 2-pole alternator having 90 slots and three conductors per slot.

The winding of each phase has 88 conductors distributed between 30 slots, the voltage generated per conductor being 217. The phase voltage and the maximum voltage to earth is 19 080.

The "bull" conductor potentials range from 19 080 volts to 13 000 volts, the "inners" from 13 000 volts to 6 500 volts, and the "outers" from 6 500 volts to zero. It is clear that with such a design there is a substantially constant potential difference of 6 500 volts between the conductors in any one slot, and a maximum voltage from the conductor to earth of 6 500 volts. Such voltages are moderate and are readily dealt with.

The conductors are arranged in three rows as shown in Fig. 6, such an arrangement being found specially suitable for a high-tension machine. By staggering the conductor slots the flux density in the stator teeth is kept uniform, and it was found possible with this design, instead of providing an elongated conductor, as for a low-voltage machine, to use the round form above described and, at the same time, obtain increased internal reactance.

By adopting this arrangement it is not necessary to bend the core conductors where they project from the stator, in order to provide a reasonable leakage gap between the end-windings and the rotor end-caps.

The staggering of the slots gives a uniform distribution of winding, and in effect has the advantages of the smooth-core armature, without the disadvantages of an unduly increased air-gap. The excitation energy is therefore retained at a very reasonable figure.

It will also be seen from Fig. 6 that the conductor ends are accessible, giving greater space for sweating and insulating the joints.

Several interesting problems were met in the manufacture of the conductors, but it is unnecessary in this paper to describe the mode of manufacture. It may be sufficient to mention that the "bull" conductor was made in the same manner as an ordinary cable, and varnish-impregnated *in vacuo*. The cable was cut into the requisite lengths, and alternate layers of mica and insulated copper strands were applied. After the application of each thickness of insulation the conductors were re-impregnated *in vacuo*. In no part of the manufacture were the conductors in any way bent.

From Fig. 7 it is seen that two slots per phase contain only two conductors instead of three; a detail of the conductor is shown at "B" in Fig. 3. The conductors of the highest potential are not carried to the slots adjacent to another phase. This increases the distance between regions of maximum potential, and so minimizes the electrical stresses. This reduces to 28 000 volts the voltage between adjacent conductors projecting from the core.

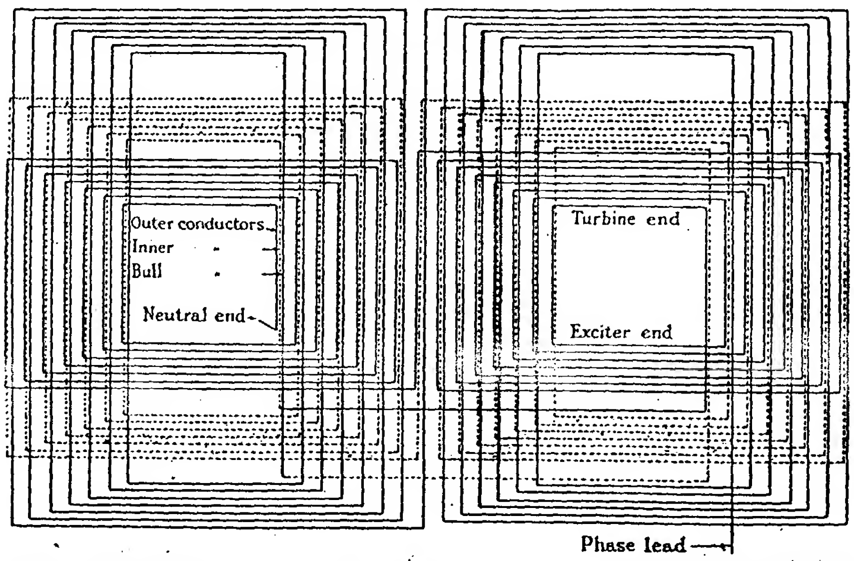


Fig. 4.—Stator winding diagram (one phase only) of a 3-phase, 2-pole winding with 90 slots and 264 conductors, 3-core concentric conductor.

The end-windings illustrated in Fig. 8 are composed of flat copper strip formed on edge and having a full radius on the edges. This formation gives a very rigid construction, enabling it to withstand the stresses set up on short-circuit. Additional mechanical support is given to the end-winding strips by fitting them into recesses formed in the impregnated-wood supporting clamps.

There are three banks of end-connections in each phase, corresponding to the "bull," "inner" and "outer" conductors. The cross connections between each bank are provided with removable links to enable each third of the phase to be pressure-tested separately. The link forms a ready means to fit between-turns protection if desired.

Ample distance is provided between phases, so that it is unnecessary to provide insulating shields between the end windings, and adequate leakage surface is also provided over the impregnated-wood packings between the phases.

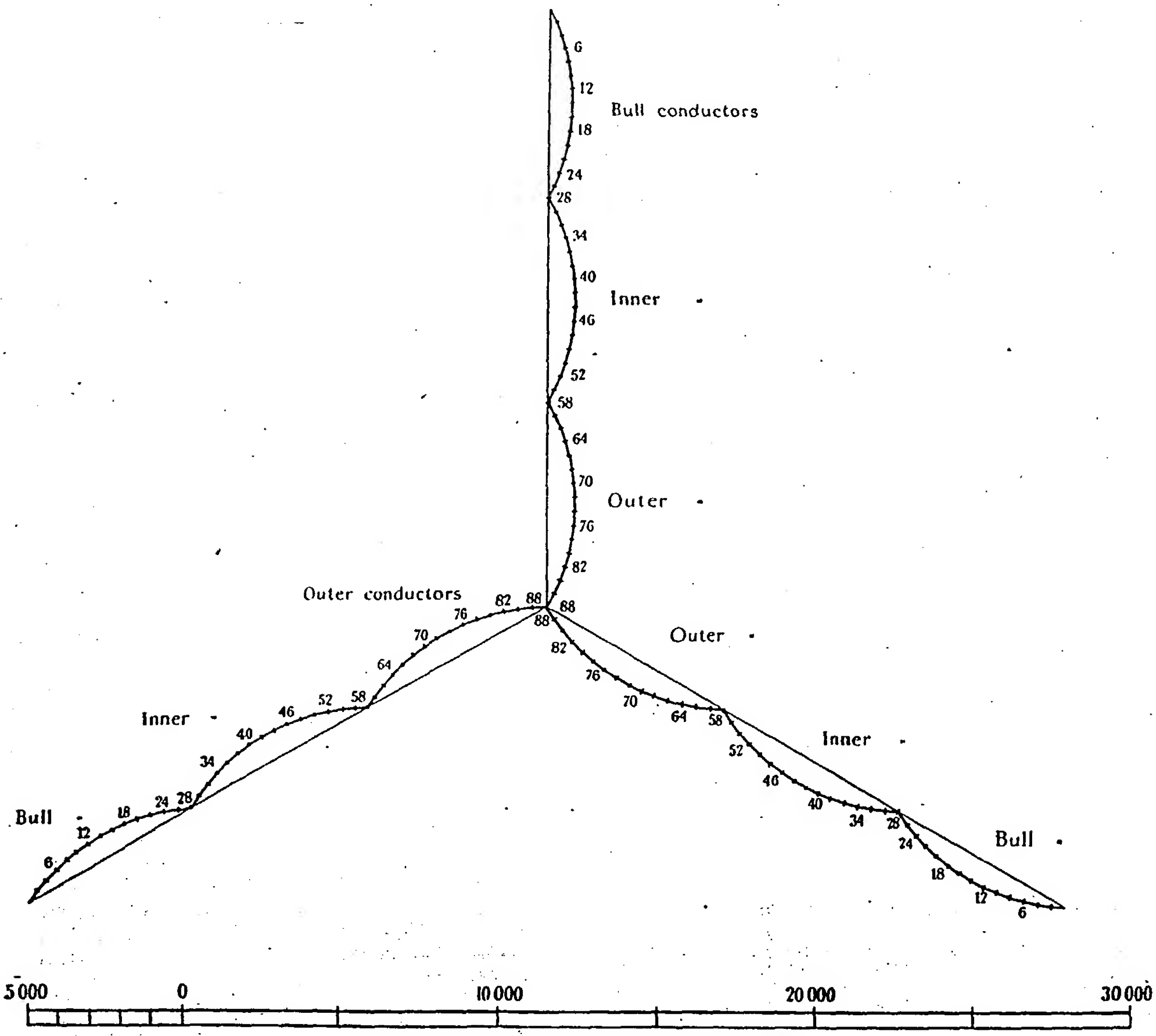


FIG. 5.—Vector diagram of conductor voltages.

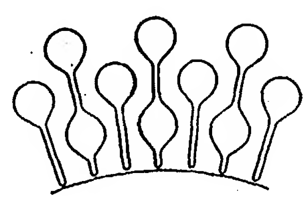


FIG. 6.—Conductor slots arranged in three rows.

In a normal design of alternator the full phase potential exists between banks in the end-windings. In the high-voltage alternator design the end-connections for the "bull" conductors of one phase are adjacent to the

end-connections joining the "outer" conductors of another phase. The difference in potential between the phase banks is therefore less than the normal voltage between phase terminals. Thus the maximum potential difference in the end-windings between the adjacent conductor No. 1 in any phase and No. 58 in another phase is, from Fig. 5, referred to above, only 23 000 volts.

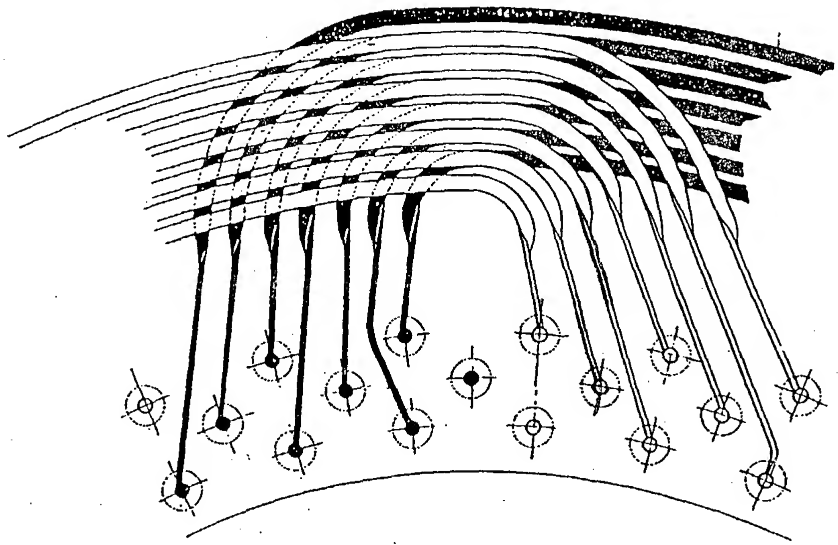


Fig. 7.—Position of highest-potential conductors relative to adjacent phases.

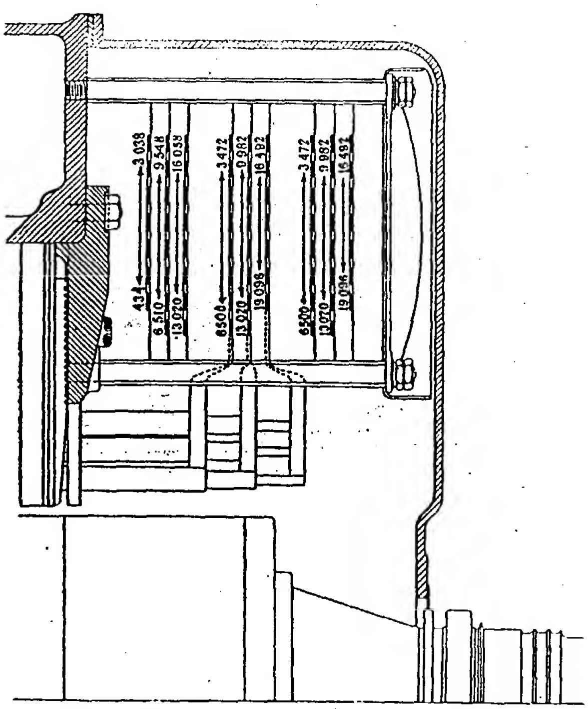


Fig. 8.—Diagram showing voltages of end-winding connections of 33 000-volt alternator.

A 25 000-kW, 31 250-kVA, 33 000-volt, 3 000-r.p.m. alternator incorporating these principles was built for the North Metropolitan Electric Power Supply Co., Ltd., for installation in their new power station at Brimsdown, North London. It has been used as a basis in describing above the features of the winding. A part cross-section of the stator and elevation of the end-winding is shown in Fig. 9.

Apart from the stator windings and mechanical details, which have been modified in order to meet the special features in the design, this alternator is of standard construction.

A short account of some of the original experiments is given, together with a few notes upon the tests made during construction and on completion.

(7) An Outline of the Experimental Research Carried out in the Development of the 33-kV Alternator, and Tests on the Completed Alternator at Newcastle. Operating Experiences on Site.

Any departure from accepted design, however small, can only be accomplished successfully after extensive research. This is particularly so in large electrical apparatus, where, in addition, the proof of actual operation must be applied. A few of the tests previous to and during the assembly of the alternator are outlined below.

Stator tooth-heating test.—A section of the core plate was assembled and wound with a temporary winding in order to check the local heating which might result from the staggered disposition of the stator slots. The temperatures did not exceed those of an alternator of low voltage.

Pressure-testing apparatus.—A single-phase transformer with a voltage ratio of 440/110 000 was used for all pressure tests. Tappings were brought out at one-third and two-thirds of the maximum voltage.

In order to overcome the liability to flash-over at the pressure test of 100 000 volts, individual bars while under test were immersed in a bath of varnish.

Test conductor bars were constructed, one set being un-impregnated and a second set being impregnated after the application of each insulating tube. The latter bars, as seen from Fig. 10, had 30 per cent lower dielectric loss.

The distribution of electrostatic capacity between the three conductors is given in Table 2.

The corresponding figures for a single conductor bar of an 11 000-volt alternator of similar output is 0·00024 μF per foot run obtained from test, the calculated value being 0·00028 μF per foot run.

Reliability tests extending over several months were made on the test bars, and an extract from the log is given in Table 3.

The potential gradient across the insulation in single-core and 3-core cables, with the same sectional areas, is given in Figs. 11 and 12. It will be seen that the maximum gradient is considerably less in the 3-core concentric cable. Flaws, such as cracks, or air pockets,

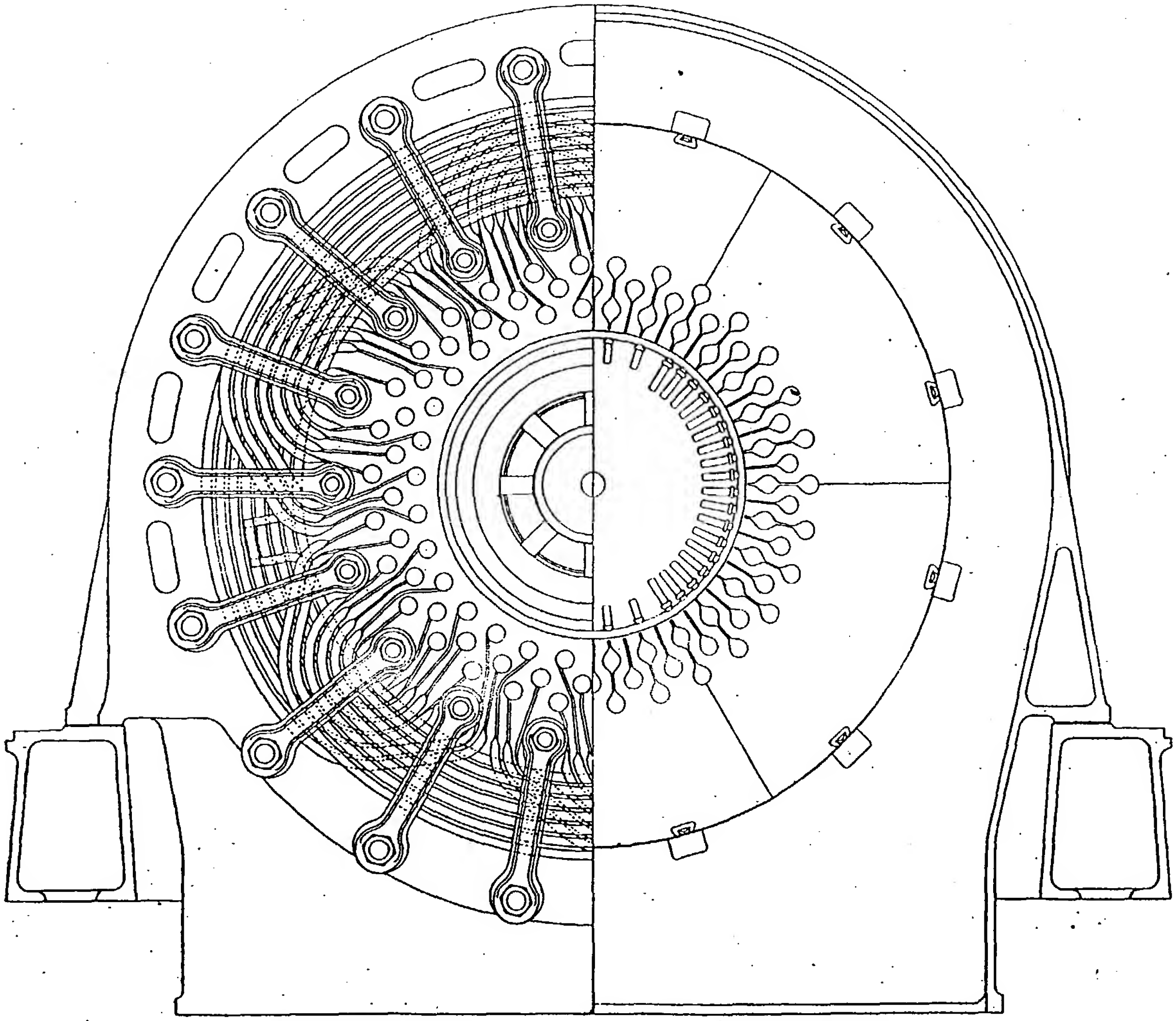


FIG. 9.—33 000-volt, 3-phase, 2-pole, 3 000-r.p.m., 31 250-kVA alternator.

TABLE 2.

Capacity per Foot Run.

Position	Concentric bars	
	Measured capacity	Calculated capacity
	μF	μF
Between " bull " and " inner " ..	0·00018	0·00025
Between " inner " and " outer " ..	0·0003	0·0005
Between " outer " and " sheath " ..	0·00034	0·00046

are less liable to occur in the concentric cable, as the layers of insulation are much thinner.

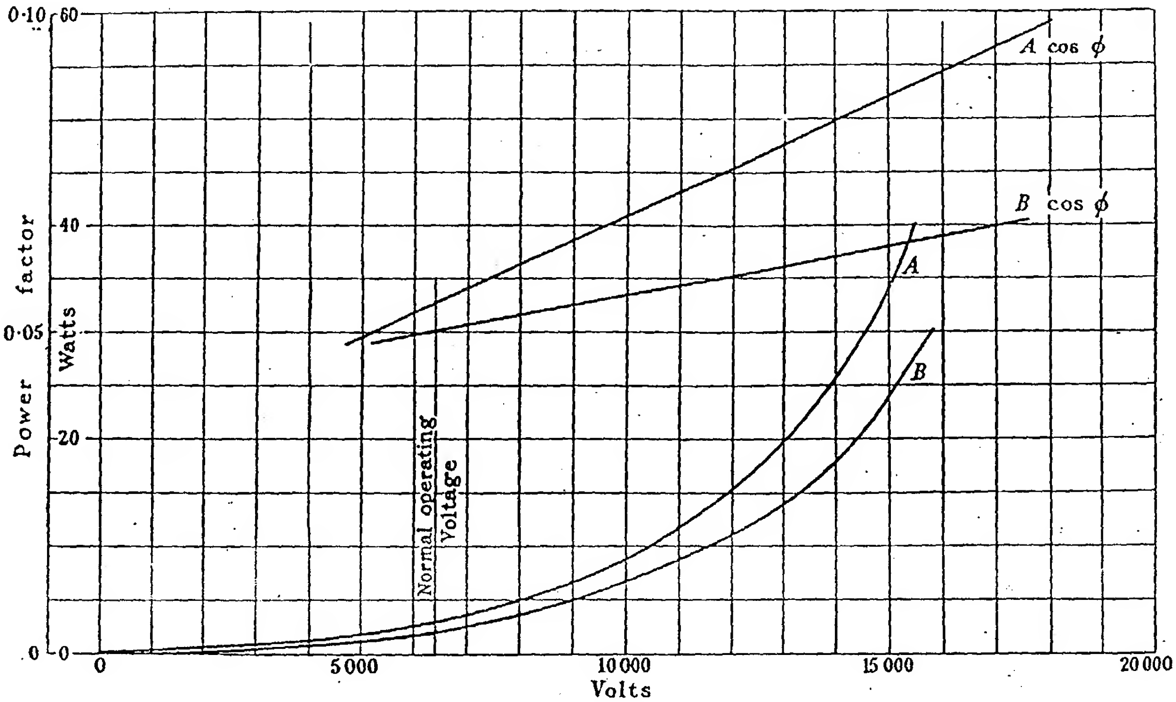


Fig. 10.—Comparative curves showing losses and power factors of concentric conductors at various voltages.
A. Un-impregnated. B. Impregnated.

Pressure tests.—On the completion of the winding the following pressure tests were applied:—

"Bulls"—67 kV between phase terminals and to earth.

"Inners"—45 kV between phase terminals and to earth.

"Outers"—23 kV between phase terminals and to earth.

Table 3.

Average Dielectric Loss in the Bar.

Test conditions	Voltage		Bar temperature 20° C.	60° C.	110° C.
33 kV on "bull" .. .. .. 22 kV on "inner" .. .. .. 11 kV on "outer"	174 per cent	Dielectric loss Leakage current	30 watts 0·008 amp.	105 watts 0·016 amp.	235 watts 0·03 amp.
19 kV on "bull" .. .. .. 12·8 kV on "inner" .. .. 6·4 kV on "outer"	Normal	Dielectric loss Leakage current	14 watts 0·001 amp.	18·8 watts 0·004 amp.	61 watts 0·008 amp.

Testing arrangements.—The alternator was erected in the shops on a specially designed test-bed. It was driven from an 800-kW steam turbine and coupled in parallel with a 750-kW d.c. motor driving through gearing. Either machine was capable of driving the alternator at full speed when fully excited. A completely enclosed air system, with a fan delivering 40 000 cub. ft. of air per minute, and surface air cooler, was provided for cooling the alternator.

Temporary air ducts were constructed, to re-circulate the air. The excitation was provided by a d.c. generator.

The open-circuit and short-circuit characteristics are shown in Fig. 13, and voltage oscillograms in Figs. 14 and 15.

Wave-form.—The voltage wave-form between phase terminals and between phase terminals and earth departs less than 1 per cent from a pure sine wave, and is free from ripples; no difficulty due to

harmonics when operating on a cable network has been experienced.

Sudden short-circuit test.—The alternator was suddenly short-circuited by an ironclad, oil-immersed switch, and an oscillogram was obtained of the current in three phases, the curves being shown in Fig. 16. It should be recorded that after the test the end-windings showed no sign of movement.

Heat runs.—As it was impracticable to dissipate

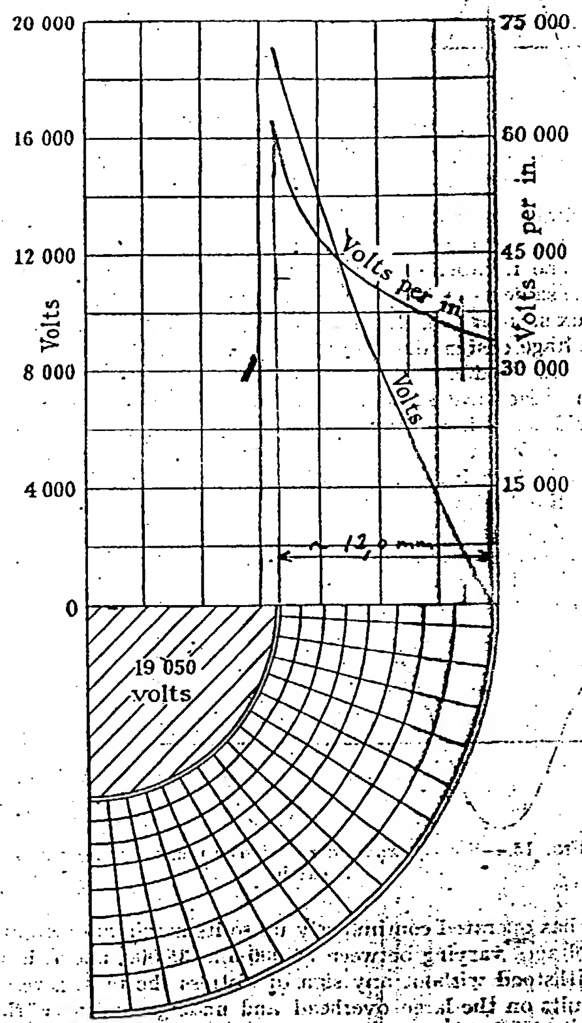


FIG. 11.—Curves showing gradient and voltage-drop across insulation for a single-core conductor.

25 000 kW at 33 kV, the windings were rearranged so as to circulate current, i.e. with the three sections of each phase in parallel. The difference in voltage between the "bull" section and the other two sections causes a circulating current which is controlled by a choke in the circuit. While the conditions do not represent the actual conditions of operation, they give a very good indication of the results to be expected on load.

The temperature-rises were moderate and very satisfactory, the figures on load being well within the estimated values.

During the open-circuit tests, a record of the leakage current per phase was taken. This figure was 80 mA at 33 kV at 60° C.

Efficiency.—The efficiency of the alternator is shown by the curve in Fig. 17. The efficiency is high at all loads, in spite of the restrictions imposed on the design owing to the fact that the machine had to be interchangeable as a whole with the low-voltage alternator.

Reactance and mechanical stresses on sudden short-circuit.—The reactance of the high-voltage alternator

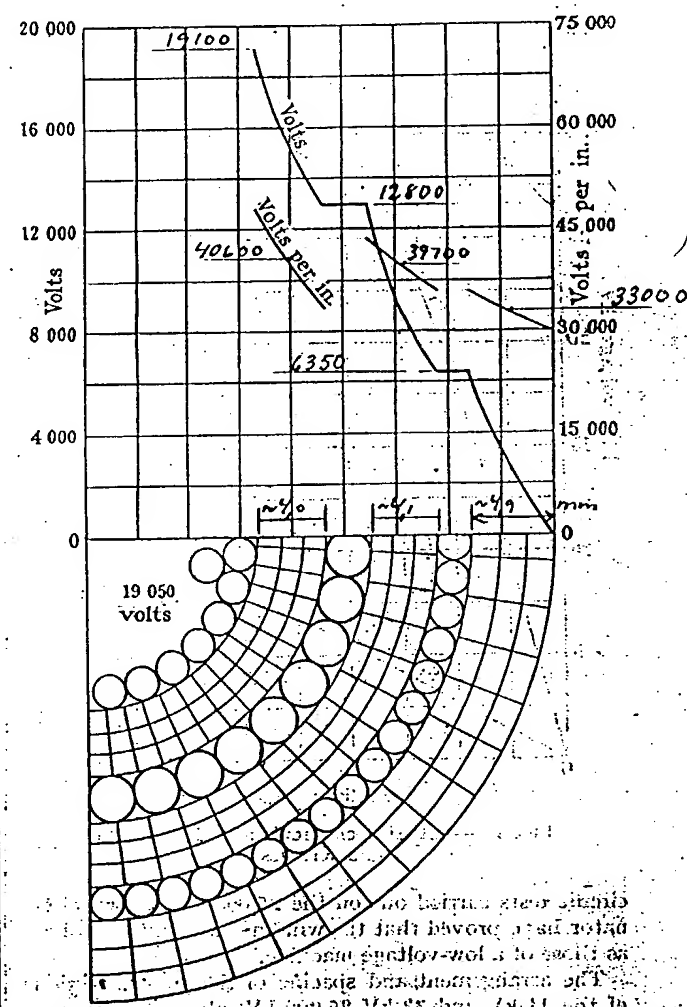


FIG. 12.—Curves showing gradient and voltage-drop across insulation with concentric conductors.

proved on test to be approximately equal to the combined reactance of an alternator of normal design and a step-up transformer. The actual value obtained by calculation is 22 per cent, and that from the short-circuit tests is 21 per cent.

Dr. S. L. Pearce, in his paper on "Prospective Development in the Generation of Electricity and its Influence on the Design of Station Plant," read before the Engineering Conference of The Institution of Civil Engineers in June 1928, draws attention to possible increased forces on the stator windings in a statement

reading as follows:—"In the absence of step-up transformers, or external reactance coils, the reactance required for limiting the short-circuit currents to values within the rupturing capacity of the switchgear has necessarily to be incorporated in the stator windings, with the natural consequence that under short-circuit conditions, the mechanical forces on inherently weaker windings are appreciably increased." In the authors' experience, this difficulty has not arisen. The short-circuit tests carried out on the 25 000-kW, 33-kV alternator have proved that the windings are quite as robust as those of a low-voltage machine.

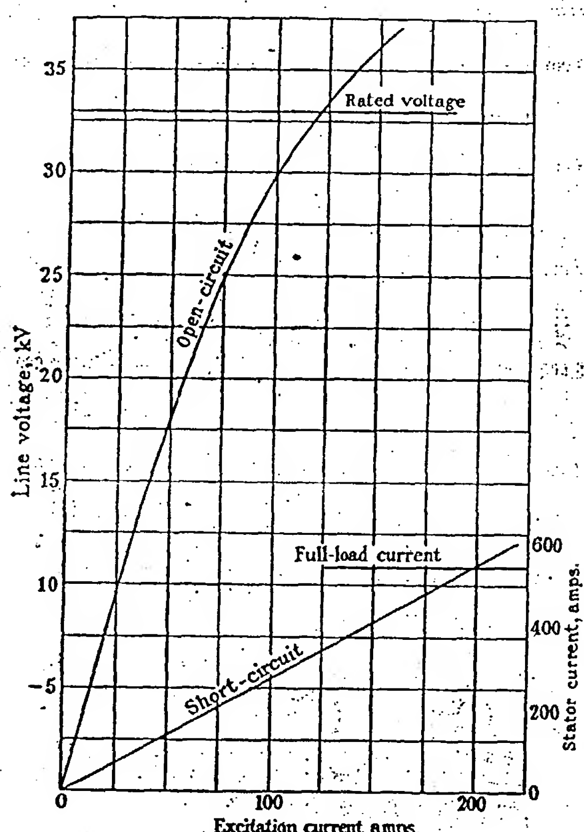


FIG. 13.—Actual open-circuit and short-circuit characteristics.

The arrangement and spacing of the end-connections of the 11-kV and 33-kV 25 000-kW alternators, respectively, are shown in Figs. 18 and 8. It will be seen that greater space is provided for the accommodation of the windings of the latter.

In making a comparison of the forces between conductors under short-circuit conditions, it is assumed that the short-circuit takes place at the terminals of the high-voltage alternator, and at the secondary terminals of the transformer connected to the low-voltage alternator.

If a short-circuit occurs at the terminals of the low-voltage alternator, the stresses in the windings are increased nearly three times.

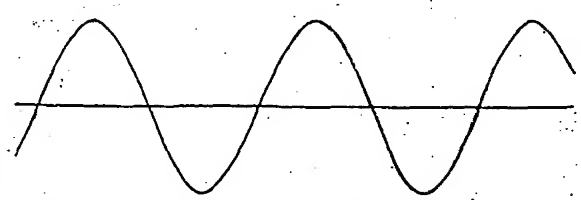


FIG. 14.—Voltage wave-form between phase terminals.

The number of ampere-conductors is approximately the same in each design, but the intensity of the leakage flux surrounding the end-windings is smaller in the high-voltage design, due to the longer magnetic path.

The conductor slots are circular and much wider than the reactance slots, and the intensity of the leakage field is low in the former. For these reasons, and owing to the lower current per conductor, the stresses between conductors both in the core and end-winding are lower in the high-voltage design than in the low-voltage design.

A comparison of the reactance and stress in the two designs is given in Table 4.

On site.—Since the plant was installed in August 1928, it has operated continuously up to its maximum load at voltages varying between 34 000 and 35 000, and it has withstood without any sign of distress the most severe faults on the large overhead and underground network to which it is coupled.

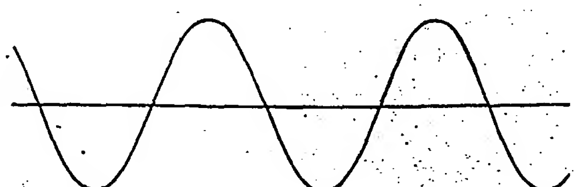


FIG. 15.—Voltage wave-form between phase terminals and earth.

The control and regulation have proved eminently satisfactory in every way.

Some extracts from the station log are given in Table 5.

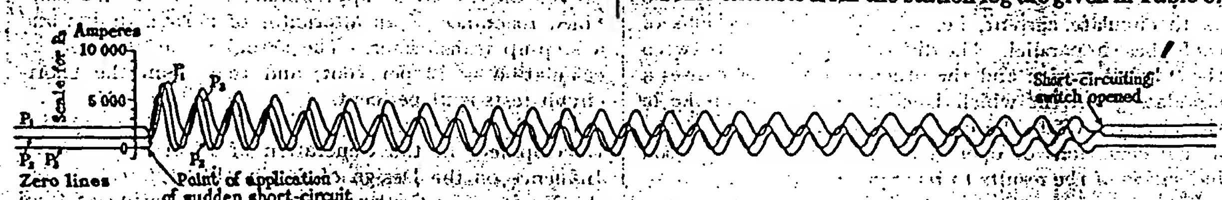


FIG. 16.—Stator currents on applying a sudden 3-phase short-circuit to alternator when excited to 33 kV on no load at normal speed.

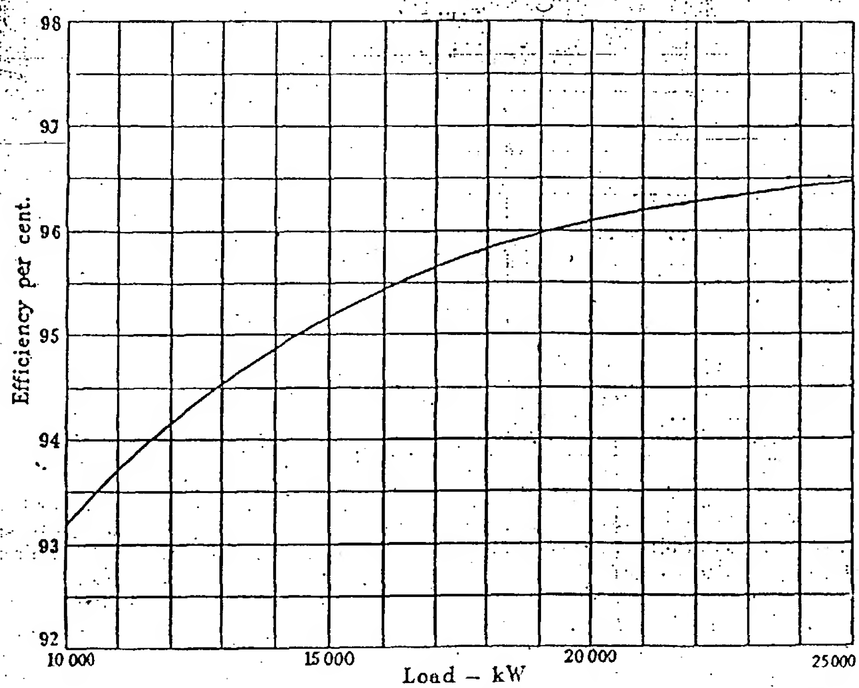


FIG. 17.—Efficiency curve of 25 000-kW, 33 000-volt, 0·8-power factor, 3-phase, 50-period, 3 000-r.p.m. alternator.

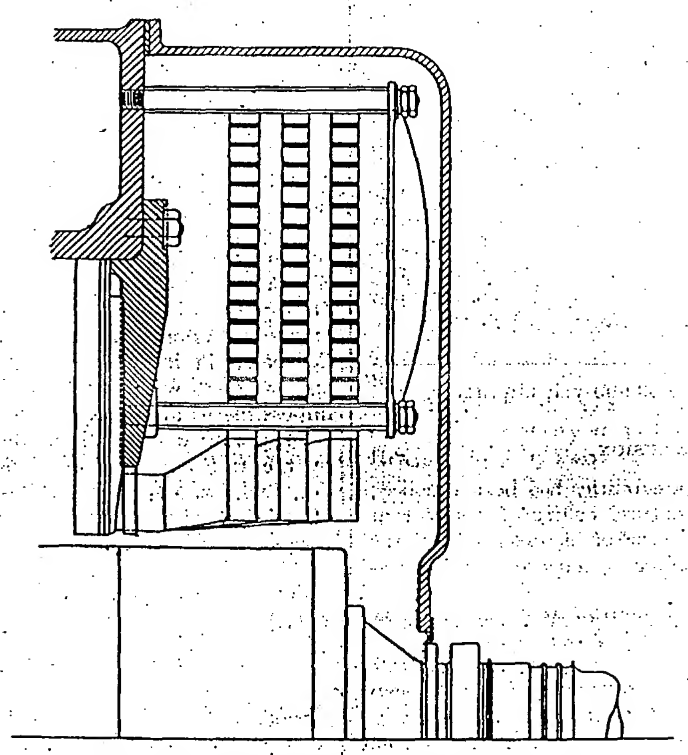


FIG. 18.—End-winding of 11 000-volt alternator.

TABLE 4.

Forces on End Windings.

	25 000-kW alternators	
	11 000 volts	33 000 volts
Inherent reactance of alternator	12·5 per cent	21·0 per cent
Reactance of transformer	8·5 per cent	—
Total reactance	21·0 per cent	21·0 per cent
Current on short-circuit	4·75 × full-load current	4·75 × full-load current
Forces in windings:—		
(*a*) End-connections between phases	75 lb. per ft. run	17·5 lb. per ft. run
(*b*) End-connections between turns	14 lb. per ft. run	2·0 lb. per ft. run
(*c*) Between core conductors	250 lb. per ft. run	140 lb. per ft. run

TABLE 5.

Extract from the Brimsdown Power Station Log. Surges on the System.

Date	Time	Generator on load	Remarks
31 Aug. 1928	01·00	No. 2	Surge
31 Aug. 1928	01·35	„ 2	Heavy surge
31 Aug. 1928	18·25	„ 2	Slight surge
19 Sept. 1928	08·30	„ 2	Heavy surge
12 Oct. 1928	10·35	„ 2	Surge
2 Nov. 1928	21·15	„ 2	Surge
5 Nov. 1928	00·06	„ 2	Heavy surge
6 Nov. 1928	19·41	„ 2	Surge
6 Nov. 1928	20·14	„ 2	Surge
6 Nov. 1928	21·01	„ 2	Surge
10 Nov. 1928	16·15	Nos. 1 and 2	Short-circuit
16 Nov. 1928	17·15	„ 1 and 2	Heavy surge
19 Nov. 1928	03·26	No. 2	Heavy surge
19 Nov. 1928	05·57	„ 2	Heavy surge
21 Nov. 1928	06·09	„ 2	Slight surge
29 Nov. 1928	17·29	Nos. 1 and 2	Heavy surge
6 Dec. 1928	14·38	No. 2	Surge

Generator No. 2 is the 33 000-volt alternator.

(8) CONCLUSION.

Only the fringe of the possibilities has been touched; it certainly seems in the natural course of design that a reliable high-voltage alternator is essential to the rapid increase in size of power systems and their interconnections.

The paper is confined to generation at higher voltages, but other units of ever-increasing size, such as motors, motor-generators, synchronous condensers, etc., may be economically designed and coupled direct to the network without the use of transformers.

Although the purpose of the authors has been to give information and to promote discussion on the high-voltage machine, their primary object is to gain from engineers an expression of opinion on the possibilities, advantages and disadvantages of generating alternating current direct at voltages higher than those now recognized as customary.

The authors hope that they have shown that a definite advance has been made in the generation of electricity and in the design of large generators which may be used for connection to the "grid." If their work contributes to the problem of providing means for the more efficient and economical generation of electrical energy, and thus to some saving in the consumption of coal, they will feel that their efforts have not been wasted.

They wish to take this opportunity of paying tribute to, and to acknowledge the courage and foresight of, Sir James Devonshire, K.B.E., Chairman of the North Metropolitan Electric Power Supply Co., and the chief engineer, Captain J. M. Donaldson, M.C., of the same Company, in installing the pioneer high-voltage unit, and without whose co-operation it would have been impossible to undertake the work.

They also wish to acknowledge the assistance given by the staff and officials of Messrs. C. A. Parsons and Co., Ltd., who have made unstinted efforts in support of all investigations and in the compilation of this paper.

[The discussion on this paper will be found on page 1117.]

Generation at 33 Kv. Proved by Performance

By J. ROSEN*

Director C. A. Parsons & Company, Ltd., Newcastle-on-Tyne, England

With a "let's look at the record" substantiation of 33-kv. generators, the author foresees a demand for alternators of 66 kv. While that waits fulfillment, the immediate possibility exists of using 2/1 auto-transformers (following the Hudson Avenue 27.6/13.8-kv. scheme) to derive 66 kv. from 33 kv. alternators without entailing double-winding transformers.

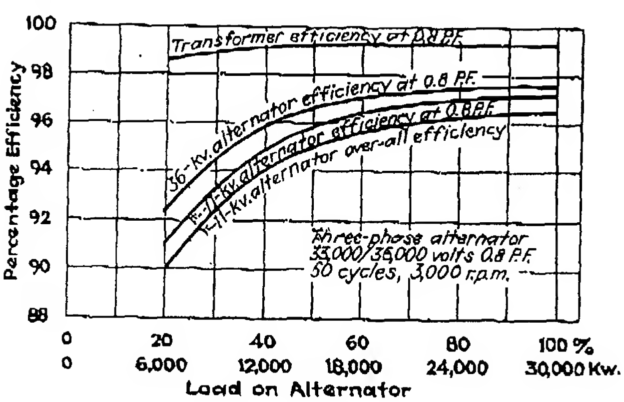
ABOUT four years ago† ELECTRICAL WORLD referred editorially to the question of generating voltages in the following striking phrases: "Generators ever grow in size, transmission lines ever grow in length and voltage, but the generator voltage remains forever. . . . Is there a law of nature or a constitutional amendment against the use of a generator voltage of over 13,800? . . . In the near future many utilities will no doubt request manufacturers to bid on 33,000-volt units and manufacturers will find means to build such units. . . . The 33,000-volt generator will come as the result of the recent tendency of public utilities to simplify their stations. It will eliminate troublesome transformation and unnecessary switching." Even while this prophecy was being penned it was already in course of fulfillment. It appeared, indeed, almost simultaneously with the inauguration of the change of practice which it foretold, and of which the advantages are now becoming more and more fully recognized.

The 13,800 volts which would appear to have been the limiting pressure at the time referred to was soon exceeded in the United States. For the 208,000-kw. unit put into service in the State Line power station in 1929 a pressure of 18,000 volts across the terminals of each of the three generators was originally proposed, but the advantages of a higher pressure became so evident that the unit was actually constructed to generate at 22,000 volts. The same pressure was adopted for the 61,765-kva. alternators built by the General Electric Company for the Super-Power Company of Illinois and also, the writer believes, for the latest 125,000-kw and 150,000-kw. units for the State Line Generating Company. As regards practice in Great Britain, it may be mentioned that although the 1,500,000-kva. turbo-alternator supplied by C. A. Parsons & Company, Limited, for testing switchgear at the works of A. Reyrolle & Company is wound for 22,000 volts, this voltage has not been favored for power station machines. The tendency has been rather to go at once to the generally more advantageous figure of 33,000 volts.

The development of turbo-alternators to generate directly at pressures of 33,000 volts and over has been brought about by both economic and technical considerations. The designer saw in higher voltages the natural solution of the problem of building ever more powerful and more efficient machines, while the power station engineer, once he was satisfied that he would lose nothing in reliability, saw that he had everything to gain by generating current at the voltage at which he needed it. Although the high-voltage turbo-alternator is a product of the last few years only, machines of this kind are now in use, or will be very shortly, by five separate undertakings. All are designed for a working pressure of 33,000 to 36,000 volts. The pioneer machine was supplied by the firm with which the writer is associated to the Brimsdown station of the North Metropolitan Electric Power Supply Company in August, 1928. It had a rated capacity of 25,000 kw. at 3,000 r.p.m. and so satisfactory was its performance that in 1931 a second machine of the same type and size was ordered for the same station. Both sets are now in regular and uneventful service.

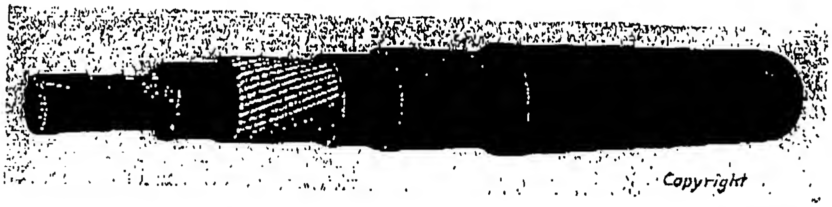
About this time interest in high-voltage generation began to be manifested on the Continent of Europe, and in 1931 a 25,000-kw. turbo-alternator was built by Messrs. Brown, Boveri & Company, Baden, Switzerland, for the Langerbrugge station in Belgium. This machine was the subject of an interesting article by F. R. Sidler in the ELECTRICAL WORLD of October 16, 1932. Circumstances in no way connected with the machine have, unfortunately, prevented it being put into service. No further developments, so far as the writer is aware, have

*All illustrations copyrighted by C. A. Parsons & Company.
†January 19, 1929.



Gain of 1 per cent in efficiency with 33 kv.

Almost half the gain is in the superior efficiency of the alternator itself and the rest in eliminating the losses in the transformer needed with 11-kv. generation.



The outer conductor comprises one-third the coil sides per phase connected in series, starting from zero or neutral potential. The 11 to 22-kv. potential level is generated by the intermediate conductors connected in series with one another and the group in series with the group of outer and inner conductors. Each layer of insulation is thus subjected to only the same 11-kv. stress it would encounter in an 11-kv. alternator of conventional design.

Triple-concentric stator conductors control flux gradient in mica insulation

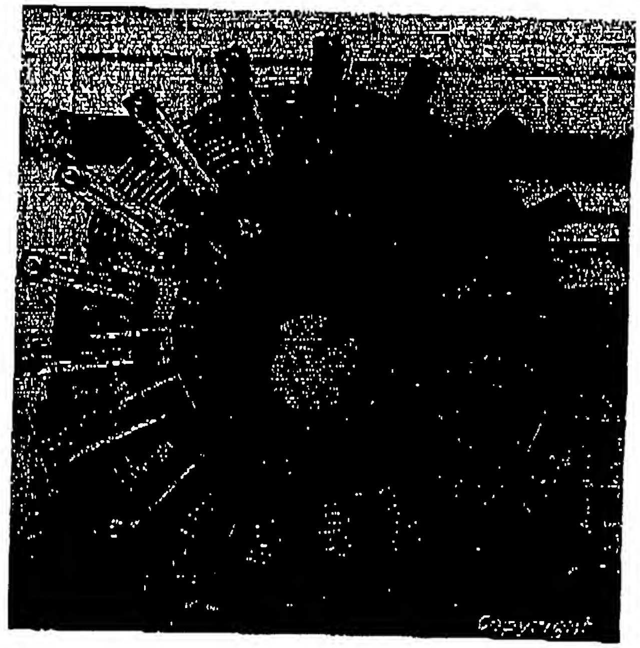
taken place on the European Continent, but early last year the corporation of Capetown ordered a 20,000-kw. Parsons high-voltage generating set, which has now been shipped to the Salt River power station of the Electricity Commission of South Africa. A duplicate plant has since been ordered by the Electricity Commission of South Africa. An 18,000-kw. alternator at 35,000 volts to replace, on the same bedplate, an existing machine wound for 11,000 volts is now being completed for a power station in South Wales.

200,000 kw. committed to 33 kv.

All the foregoing high-tension alternators were destined for service in existing stations alongside units of ordinary voltage, but when equipment of the new superstation at Swansea was decided on it was determined to generate exclusively at high voltage from the start. The Heaton Works were therefore intrusted with the construction of a pair of 30,000-kw., 3,000-r.p.m. turbo-generators to work at a pressure of 33,000 to 36,000 volts. There are thus already in existence or in process of manufacture for central-station work eight high-voltage turbo-generators of an aggregate output of 200,000 kw., of which four machines aggregating 125,000 kw. have been ordered during the last twelve months.

This rapidly increasing popularity of the high-tension generator is due mainly to two facts; it is considerably cheaper in first cost, and at the same time it is more efficient than the old arrangement of a low-tension machine coupled to a transformer. Not only are the transformer losses abolished and a risk of the introduction of harmonics into the system eliminated, but a 33,000/36,000-volt generator can be built with an inherently higher efficiency than a low-voltage machine of the same power. The difference in the case of a 30,000-kw. alternator at 80 per cent power factor will be about 0.3 per cent in favor of the high-tension machine at full load, or 1.0 per cent if the transformer losses are to be taken into account. At partial loads the differences in favor of the high-tension machines are, of course, substantially greater.

The higher efficiency of the system of high-voltage generation would alone have been sufficient, in many cases, to turn the scale in its favor, but when engineers realized in addition the saving of money and space due to the elimination of the step-up transformers, and the simplification consequent upon the reduction in size and number of the cables to be brought out from the machine, the issue was no longer in doubt. In a discussion on high-voltage generators by the British Institution of Electrical Engineers in London on January 29, 1929, Capt. J. M. Donaldson, the chief engineer of the North Metropolitan Electric Power Supply Company, stated that the savings effected on all counts by the installation of the first high-tension machine at Brimsdown were equivalent to a reduction in capital cost of more than 10 shillings ($2.43) per kilowatt of capacity as compared with an ordinary plant.



Fibrous braces replace iron for end-connection supports. Efficiency improved, handling facilitated and noise reduced

The long period of stagnation in turbo-generator voltages referred to at the commencement of this article was due to two causes: First, a fear of insulation difficulties, and, second, the ease with which any required transmission voltage could be obtained by means of transformers. Engineers still remembered the trouble with the early 11,000-volt machines arising from the formation of ozone and oxides of nitrogen and were consequently shy of any great advance in generating voltages. The flexible type of mica insulation developed by the author's firm in 1913 would have allowed higher voltages to be employed at that date, but it was felt that the maximum steeper potential gradients which would have been involved by increasing the thickness of the insulation were better avoided.

So the matter rested until the design of high-voltage machines was made the subject of a special study in 1921. It was then decided that the best solution of the problem was to be found in the use of conductor bars in the form of triple-concentric, mica-insulated cables, the outer and intermediate conductors of which would act as intersheaths as well as generating voltage and carrying current. By this device no insulation need be called upon to carry any higher stress than in an ordinary low-voltage

machine. Before a 33,000/36,000-volt alternator was constructed on this principle full sized conductor bars were tested continuously for more than two years under conditions similar to those which would exist in a machine generating 57,500 volts between phases, the conductors being electrically heated to 90 to 110 deg. C. during the day and allowed to cool off at night. No deterioration whatever of the insulation could be detected.

An objection often raised against the principle of generating directly at the transmission voltage is that the old practice of inserting a transformer between the busbars and the generator protects the latter against the effects of surges and short circuits on the transmission lines. This argument is easily met. In the first place the high-voltage alternators are designed to have the same reactance as that of an ordinary machine together with that of its transformer, so that the short-circuit current will be limited to the same multiple of the full-load current in either case. The shock, moreover, must be taken at some place, and the windings of the high-voltage machine with concentric stator bars are even better fitted to withstand it than are the windings of an ordinary step-up transformer.

End stresses greatly reduced

It must also be remembered that, owing to the smaller currents to be carried, the forces on the end windings of a high-voltage generator are very much less than the corresponding forces in a low-voltage machine. It can be shown by calculation that by raising the voltage of generation from 11,000 to 36,000 a reduction of more than 75 per cent in the forces per foot run on the end connections between phases and of more than 85 per cent in the forces between adjacent turns can be readily secured. All high-voltage turbo-alternators are, of course, subjected to sudden short-circuit tests across their terminals at full voltage before they leave the works.

In connection with the question of the protection which a transformer can give to an alternator, reference may be made to an article by W. A. McMorris of the transformer department of the General Electric Company published in ELECTRICAL WORLD, September 24, 1932.

In this article it is stated that both theoretical and experimental studies, substantiated by field work, have shown that surges due to lightning can be and are transmitted through a transformer to the running machinery, the impedance of the transformer opposing no sensible barrier to the surge. The subject is a controversial one, but if Mr. McMorris' conclusions are accepted, it would appear that a high-voltage alternator must be less severely stressed by a lightning surge than a low-voltage alternator and transformer combined.

Brimsdown installation quickly duplicated

The best proof, however, of the needlessness of a transformer to protect a high-voltage generator is to be found in the experience at Brimsdown. The first of the two high-voltage alternators in this station has now been working continuously for about 4½ years at a pressure of about 34,500 volts. It feeds directly into an overhead system extending for 60 miles and connected by long underground cables to an overhead system of another company. Very soon after its installation an unprecedented series of faults occurred on the transmission lines, resulting in almost daily surges up to short-circuit intensity. No harm whatever was done to the machine, which, when opened up for a thorough examination after three years of service, was found to be in perfect condition. It should be noted that, contrary to certain statements which have gained currency, this machine is working, and has always been working, with its neutral point insulated from earth, so that the conditions in the event of a fault on the system are the severest possible.

The second high-voltage alternator at Brimsdown, though identical in general design with its predecessor, embodied an improvement which is now being incorporated in all high-voltage machines. This consists in the use of end shields of a fibrous material instead of the usual cast iron. The new type of end shield, being non-magnetic and non-conducting, enhances the efficiency of the alternator by the avoidance of eddy currents. For the same reason the shields can be attached rigidly to the end-winding bolts, a procedure which conduces to silence in operation. Their lightness, moreover, is a considerable convenience when it is desired to open up the machine for examination.

The next step is 66 kv.

The next few years will almost certainly see a demand for turbo-alternators to generate directly at 66,000 volts. The development of the concentric conductor principle has already brought them within the range of possibility. Meanwhile, however, it may be pointed out that the existence of the 36,000-volt generators makes it practicable to attain a transmission pressure of 66,000 volts by means of auto-transformers. While this would not be so economical as direct generation at the higher pressure, it would be both much cheaper and more efficient than the present practice of using ordinary low-voltage generators and double-wound transformers.

The advantages of using auto-transformers in connection with large generating sets is already appreciated in the United States, and credit must be given to the initiative of American engineers in this field. An outstanding example of this practice is afforded by the 770,000-kw. Hudson Avenue power station of the Brooklyn Edison Company. Here the original generators designed for 13,800 volts and the latest 16,500-volt generators of 160,000-kw. capacity are all stepped up to the busbar pressure of 27,600 volts by means of auto-transformers, without any intermediate switching. The duplication of the generator voltage by this method on so large a scale should remove the last doubt as to the feasibility of attaining a transmission pressure of 66,000 volts from 36,000-volt generators in the same way.

Addressograph for Demand Readings

Using for meter readings the addressograph that is applied to the bills is a practice followed by some utilities. H. L. Thomson, Hartford Electric Light Company, has hit upon the novel and simple scheme of handling demand register indications on the same system. Below the name, address, route, code, etc., he prints three 1's, the end ones separated from the middle one by four dots. The meter reader puts an arrow pointing to the dot corresponding to the scale position of the demand pointer and then labels the 1's to correspond to the scale marking. This avoids the necessity of estimating fractional division values. It also serves as a permanent record of the reading.

CORONA DISCHARGE ON ALTERNATORS

Notes on some interesting Experiments carried out at Heaton.

By R. H. Parsons.

AMONG the elementary experiments familiar to all students of electricity, is the demonstration that a conductor, when sufficiently highly charged, becomes surrounded by a luminous glow formerly known as a "brush discharge," but now more commonly as a "corona." This glow is caused by the ionisation of the air on account of the high potential gradient near the conductor, and the effect of the ionisation is to bring about the formation of ozone and oxides of nitrogen which are ultimately destructive to insulating materials in the neighbourhood. The deleterious effect of the corona discharge on the durability of high-tension electrical machinery has always been recognised, and fears of trouble from this cause have no doubt done much to retard the development of such machinery. The chief danger points of an alternator, so far as corona is concerned, are where the conductor bars emerge from the core of the stator, and to a lesser extent, where the same bars cross the internal ventilating slots. At these places there is a concentration of the electrostatic field on the comparatively sharp angles of the iron core, with the result that high potential gradients exist in the air surrounding the insulation of the conductors at such points. Corona discharges are set up as soon as the potential gradient exceeds about 53,000 volts per inch, and this fact imposes a fairly definite limit to the voltage for which a generator of the ordinary type can be designed without exceeding practical proportions of conductors and insulation, and having due regard to safety and durability. This limit may be put at about 22,000 volts between phases, although by a reduction of the test pressure usually specified, and by the adoption of certain expedients, such as the use of intermediate condenser sheathings in the insulation, one could build machines of usual type for somewhat higher voltages.

Since the danger of corona is essentially due to the potential difference between the conductors and the stator core, there is little scope for increasing the generating voltage of an alternator of the ordinary design much beyond the figure given. If, however, instead of employing the usual type of single conductor, the conductors are arranged concentrically one within the other, the generating voltage may be raised to any desired value without involving conditions under which corona can occur. All high-voltage alternators now in service, with one or two exceptions, are therefore constructed on the concentric conductor principle. With the usual triple-concentric conductor the voltage to earth is at once reduced to one-third of that to be supported by a single-core conductor, so that machines working at 36,000 volts are subjected only to the same electrical stresses, and in consequence are as free from the danger of corona discharge as ordinary 12,000 volt generators. Indeed, so far as electrical stresses are concerned, whether in the insulation or in the surrounding air, the voltage of the concentric conductor type may be as many times greater than that of an ordinary machine as the number of cores per conductor.

The theoretical advantages of windings on the concentric conductor principle in minimising electrical stresses have always been beyond dispute and practical experience has confirmed their immunity from corona effects since the first high-tension turbo-alternator was put into service in 1928. It was, nevertheless, thought worth while to carry out tests on an actual machine with such windings, in order to verify the absence of corona under working conditions, while further experiments were designed to determine the voltage at which corona would commence around conductors of the kind employed. The machine selected for the first-mentioned tests was a high-tension alternator recently completed by Messrs. C. A. Parsons & Co., Ltd., to the order of the Electricity Supply Commission of South Africa for service in their Salt River Power Station. The unit, which was the third of the same kind to be built for this station, had a rated capacity of 20,000 kW at 3,000 r.p.m., and was designed to generate at 35,000 volts. The alternator, together with its turbine, was erected on the test beds at the Heaton Works for the usual official tests and inspection by Messrs. Merz and McLellan, the consulting engineers to the Electricity Supply Commission. After the completion of these tests, the corona discharge tests were carried out, these being also witnessed by the representatives of the consulting engineers. The time chosen for the corona tests was after five o'clock in the evening, when ordinary work had ceased for the day. The hour had the further advantage that as it was in the depth of winter, and daylight had long since vanished, there was no difficulty in keeping the test house in complete darkness. To prepare the machine for the tests, the end shield of the alternator remote from the turbine was removed and replaced by a sort of tent of tarpaulin arranged to cover the whole of the end-windings, slip-rings, pedestal and exciter. This tent also accommodated the observers together with a photographic camera.

The machine was first run up to its normal speed of 3,000 revolutions per minute, and the observers took their places under the tarpaulin cover. Then, in order to provide a means of checking the exact position of any corona which might be registered on subsequent plates by the camera, a photograph was taken of the end-windings illuminated by a 1,000 watt lamp. The camera was left in position and the light switched off. After a wait of about fifteen minutes for the eyes of the observers to become accustomed to the darkness, the alternator was excited to 33,000 volts, and a fresh plate was exposed in the camera for a period of four minutes. No signs of corona were visible to the observers, and the total absence of any discharge was confirmed when the plate was developed later. During the test a very slight sparking had been perceptible at the slip-ring brushes, and to eliminate any effect this might have had on the observers' eyes in the otherwise complete darkness, the test was repeated after the windows in the slip-ring casing had been covered with presspahn, but still no signs of corona could be detected. The alternator voltage was then raised to 36,000 volts and another four-minute photograph taken with the full aperture of the camera. As before, the developed plate was absolutely blank.

These tests fulfilled their immediate purpose in showing that no corona discharge took place at the highest working voltage of the machine, but they left unanswered the question as to what voltage would be sufficient to bring about a discharge on windings of the type employed. To determine this point, Messrs. Parsons undertook a further series of tests on models of the end-windings of a high-tension alternator. Preliminary tests on a straight copper bar of the same cross-section as the end-windings, and insulated for half its length in exactly the same way as the windings, showed no trace of corona at 21.2 kV—the maximum voltage to which the windings would be subjected in a 33,000 volt machine. Visible corona started just before 40 kV was reached, and further discharges took place at 67 kV, but no very definite conclusions could be drawn from these experiments, as the discharges depended upon the state of the end of the bar, and the conditions peculiar to the tests. For this reason it was decided to carry out tests on a full-sized replica of one of the end-turns of the inner bank of a high-tension alternator winding, the turn chosen being that which passes nearest to the supporting stud. A sector of the coreplate was reproduced in wood, sprayed with aluminium to render it conducting, and a stud and insulating stud-tube fixed perpendicular to its face. The end-turn, exact as to size, shape and insulation, was supported at the correct distance from the coreplate by oil-impregnated blocks of beech wood.

The model was erected in the dark room, and photographed with four-minute exposures, at 21.2 kV, 42 kV, and 62.5 kV respectively. No corona was registered at 21.2 kV or 42 kV. After 50 kV had been passed, corona began to appear round the tube forming the insulation of the stud, and at 62.5 kV several discharges occurred which were also photographed for subsequent careful study.

This series of tests, in which were reproduced the severest conditions occurring in practice, provided complete assurance that no corona discharge need be feared in the end-windings of a machine of the concentric conductor type designed for a working pressure of 36,000 volts between phases, until the windings are subjected to a voltage slightly above 50 kV (r.m.s. value) to earth. Since as has already been pointed out, the maximum voltage which the windings of such a machine would have to stand in service is only 21.2 kV to earth it follows that the danger limit is not reached until the voltage reaches about 250 per cent. of the working pressure. Thus the factor of safety is most ample, and the general realisation of this fact should bring nearer the time when advantage will be taken of the possibility afforded by the concentric conductor principle of building alternators for generating directly at the transmission pressures of 66,000 volts and over, a development which now cannot be much longer delayed.

DEVELOPMENT OF H.-V. GENERATORS

Notes on the Origin and Characteristics of the 33,000 Volt Type.

(Contributed.)

NOW that the principle of generating current directly at the net-work pressure of 33,000 volts and over has been adopted by a number of important power stations, the advantages of the system as regards both economy and simplicity may be considered as definitely established. They would, indeed, have hardly needed argument had not custom tended to blind engineers to the obvious. For what good reason could be given for generating current at the usual pressure of about 6,600 volts or 11,000 volts when it had to be sent out of the station at 33,000 volts or more? To say that the transmission voltage is easily obtained by means of step-up transformers is no answer to the question. Transformers are expensive, they occupy valuable space, they involve appreciable electrical losses, and they may introduce troublesome harmonics in the system. Moreover, in spite of their general reliability, if their presence is unnecessary, they constitute a needless source of possible trouble and breakdown.

The explanation of the practice of using step-up transformers is not far to seek. They offered at one time the only means of meeting the demand for higher transmission voltages without involving any change in the generating machinery. So well did they appear to meet the immediate requirements of the case that generating voltages entered upon a period of stagnation. The necessity for using a step-up transformer for all but the most moderate transmission voltages was taken for granted. Indeed so complacently was the position accepted that the coupling of a low voltage alternator solidly to a transformer, and the operation of the pair as a single unit was looked upon as an arrangement offering no possibilities of improvement. Yet, popular as it became, it presented obvious grounds for criticism. Two pieces of apparatus were being used to perform the duty of one, with consequently increased costs in terms of money, space and efficiency. From the electrical point of view, moreover, the scheme had a grave defect. As every electrical designer knows, heavy currents are liable to cause more trouble than high voltages, and the heavy currents in the alternator windings necessitated by the low voltages became more and more difficult to deal with as greater powers were called for.

Fig. 1. The Second High-Voltage Machine installed at Brimsdown.

Fig. 2. Method of Making Joints between Core Conductors and Strip End Winding.

As long ago as 1921 these considerations were in the minds of Sir Charles Parsons and his colleagues, who realised that developments in the direction of higher generating voltages would not only be advantageous on the grounds of economy and simplicity, but would become inevitable with the increasing size of machines. They realised also that the only serious argument which the forces of conservatism or prejudice could bring against the advances would be the claim that higher generating voltages could only be obtained at the sacrifice of safety and reliability. It is true that experience had shown that an 11,000 volt machine could be every bit as reliable as one built to generate at 6,000 volts, but whether the same factor of safety could be secured if the pressure were raised to 33,000 volts or more was an open question. Messrs. C. A. Parsons & Co. therefore determined to look thoroughly into the problems of high voltage generation, taking reliability as their criterion of design. That there might be no doubt on this matter they decided that only their ordinary, well proved methods of insulation were to be admitted and that the insulating material should never be called on to work under any severer conditions than those safely withstood in machines of standard voltage.

Under such limitations it might appear that little or no scope remained for any advance in generating voltages. But the genius of the inventor of the compound steam turbine found a line of progress. By devising stator conductors in the form of concentric cables, and arranging that

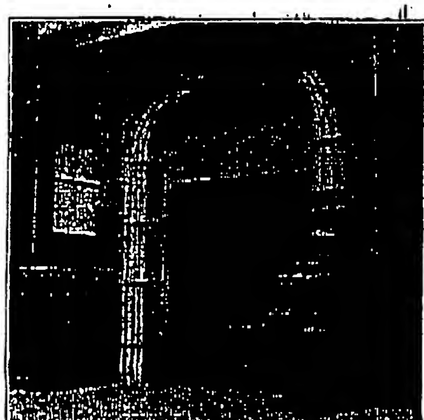


Fig. 3. Detail of End of Foundation Block, showing Large Main Cables from Stator Terminals in the case of a machine of 6,600 volts. Compare this with the higher voltage machine in Fig. 4.

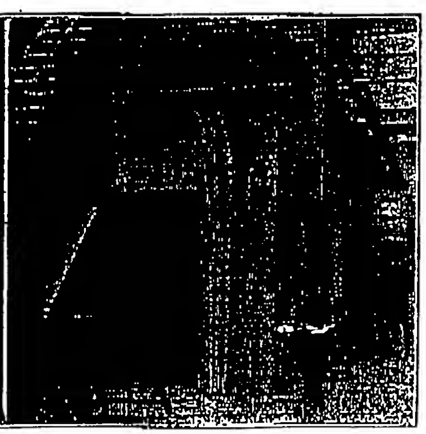


Fig. 4. Detail of End of Foundation Block, showing Small Main Cables from Stator Terminals. Note the less number of Cables and the smaller hole in foundation for a High Voltage Alternator.

the intermediate and outer layers of wire served both as inter-sheaths and as carriers of current, Sir Charles and his colleagues solved the problem in a simple and effective way. The intermediate layers of insulation, being no thicker than the insulation of ordinary machines and being subject to no greater potential gradients, would be working under conditions known by experience to be absolutely safe, although the total voltage generated might be many times that of ordinary practice. By the use of concentric conductors it appeared feasible to build a machine

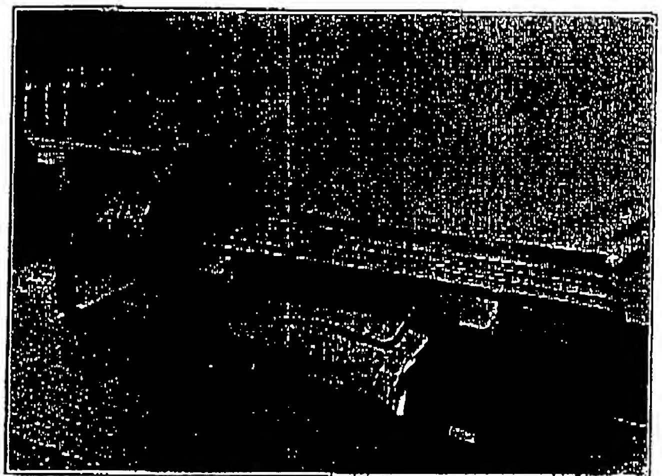


Fig. 5. Comparison of leads for 6,000 volt and for 36,000 volt Alternators. The small lead (on paper) in foreground is designed for the 36,000 volt machine and carries the same load as each of the large leads which are for 40,000 kVA.

to give a terminal pressure of at least 36,000 volts between phases without the insulation being more highly stressed than in the ordinary 11,000 volt machine.

The insulation of the slot conductors having thus been placed beyond doubt, there remained the question of the end connections. These have often proved a source of trouble in ordinary machines on account of the large magnetic forces to which they are subject. The high voltage alternator, with its much smaller currents, starts with obvious advantages in this respect. Calculations showed, indeed, that by raising the voltage of a machine from 11,000 volts to 33,000 volts, a reduction of more than 75 per cent. in the forces per foot run on the end-connections between the phases, and of over 85 per cent. of the forces between adjacent turns could be brought about.

The stiff, straight, projecting ends of the slot-conductors, moreover, would not only lend themselves to a sound mechanical connection of the end-turns, but would contribute greatly to their rigidity. A high-voltage alternator should therefore be inherently better able to withstand heavy surges and short-circuits than a low-voltage machine. In this connection it may be remarked that the practice of using a low-voltage alternator in combination with a step-up transformer is frequently defended on the ground that the transformer acts as a " buffer " which preserves the machine from injury in cases of surges or short-circuits on the system. But the shock has to be taken somewhere, and the windings of a high voltage generator of the concentric conductor type are even better able to support it than are the windings of the average step-up transformer. Furthermore, since the reactance of the high voltage machine can easily be made the same as that of the combined transformer and low voltage alternator, the short-circuit current can be limited to the same multiple of the full-load current with either type of plant.

The principle of direct generation at high voltages having been demonstrated to be sound and practicable so far as calculations and drawings could furnish proof, it remained to put the proposed constructional methods to the test of actual experiment. Several important points had to be investigated, there was the possibility that, in spite of calculations, the escape of heat from the central core of the conductor might be inadequate; that the insulation might deteriorate under its special conditions of duty, or that the temperature changes inevitable in service might give trouble by the consequent differential expansion and contraction of the concentric conductors. Too much was at stake for any chances to be taken, for an initial failure or even a disappointing performance of the pioneer machine might have had disastrous results on progress. Moreover, a reputation for reliability dating from the construction of the first turbo-dynamo and the first turbo-alternator in the world was not to be lightly risked. Hence, in accordance with the customs of the Heaton Works, full-scale experiments were undertaken in connection with every new constructional detail, the work being commenced in 1922.

The manufacture of the triple concentric conductors presented no special difficulty, as stranded conductors had long been used in the firm's turbo-alternators. The process of manufacture was that adopted for ordinary concentric cables, with the difference that the insulating layers were formed of mica. A special flexible varnish, as employed by the firm for many years to withstand stresses due to temperature changes, was also employed. One of the conductors, so prepared, was submitted to a most exhaustive series of tests. Pressures of 33,000 volts, 22,000 volts, and 11,000 volts were applied respectively to the central, the intermediate, and the outer elements of the conductor. Under such conditions, it should be noted that the conductor was supporting a voltage equal to that which would be developed in the conductor of an alternator working at no less than 57,500 volts between phases. These conditions were maintained for three consecutive months with the conductor at atmospheric temperature, and continued for many months more with the conductor electrically heated to 90° C. or 110° C. during the day, and allowed to cool at night.

The object of the latter test was, of course, to imitate the temperature changes which might occur in service. But to reproduce more accurately the working conditions of a stator conductor, and to maintain a closer supervision over the behaviour of the insulating material, a conductor bar of normal type was embedded in a core of laminated iron representing part of the core of a full-sized stator. This bar was maintained for more than a year at a pressure of 22,000 volts, the insulation thus being stressed as highly as in a machine working at 38,000 volts between phases. The temperature of the bar was caused to vary in the manner described above. During the whole of the time the dielectric losses were kept under continuous observation. They were found to be constant, thus showing that no deterioration occurred in the material embedded in the iron, nor could any deterioration be detected in the insulation where the conductors emerged from the core—always a critical place.

These experiments made abundantly evident that the design of a machine to operate at the standard network pressure of 33,000 volts could be proceeded with free from any anxiety as to the efficiency or the durability of the insulation. But there were other points to be considered. In the provisional design of the stator core the slots were arranged in staggered formation and there was the possibility that this might give trouble from local heating. So a section of core-plates was assembled and wound with a temporary winding to settle the question. Any doubt proved groundless, for no more heating occurred than in the core of an ordinary low voltage alternator. The electrostatic capacity of the several windings of a concentric conductor with respect to each other was also measured and found equally satisfactory.

There was thus no room left for questioning the practicability of constructing turbo-alternators of the new design, capable of generating very high voltages with perfect safety and exceptionally high efficiency. The first opportunity to supply such a machine was given by the North Metropolitan Electric Power Supply Company, who decided on the advice of Captain J. M. Donaldson M. C. their chief engineer, to install a 25,000 kW unit to operate at 33,000-36,000 volts in their Brimsdown station. The order was placed in 1926, but owing to the effects of the coal strike in that year there was considerable delay in getting the station to work, and consequently the new machine could not be put into service before August 1928.

In preparing the design it was decided to use the same insulation on the concentric conductors of the stator as the tests above described had shewn to be adequate for a machine working at 57,500 volts between phases. The individual layers, moreover, would not be stressed more highly than was customary in any ordinary 11,000 volt machine. Hence absolute confidence could be felt in the result, and this was confirmed by the severest tests at the works. The conductor-bars were tested individually at 100,000 volts, and when the winding was completed the central conductors were tested at 67,000 volts both between phases and to earth, similar tests of 45,000 volts and 23,000 volts being applied to the intermediate and outer conductors respectively. The finished machine was driven on the test bed either by an 800 kW turbine or a 750 kW D.C. motor, either being capable of driving it at full speed when fully excited. A completely

enclosed ventilating system, comprising an air-cooler and a motor-drive fan delivering 40,000 cu. ft. of air per minute was provided for cooling the alternator.

The machine could not, of course, be tested at its rated output in the works, but the temperature rise under full-load conditions was determined by coupling the three sections of each phase in parallel. Owing to the differences in voltage between the sections, the required current could be caused to circulate through them, its amount being regulated by a choke in the circuit. The efficiency of all loads was good, rising to 96.5% at full load with 60% power factor. This, however, did not represent the best that could be obtained, for the machine in question had to be designed to be interchangeable in dimensions with an ordinary 11,000 volt machine. Open-circuit and short-circuit characteristics were obtained, and the leakage current at 33,000 volts was found by measurement to be extremely small. The alternator was also subjected to sudden short circuits when running at 33,000 volts and 3,000 revolutions per minute without any sign of movement of the end-windings being detectable. Its reactance was measured and found to be 21%, or approximately equal to the combined reactances of an ordinary low-voltage alternator together with its transformer. Lastly the wave-form of the voltage between phase-terminals, and from phase-terminals to earth, was recorded by an oscillograph and found to differ from a pure sine curve by less than one per cent. and to be quite free from any ripples.

After being so thoroughly tested at the Heaton Works there could be little doubt of the performance of the high-tension alternator in actual service. It fulfilled indeed the highest expectations. It was started in August, 1928, with the responsibility of the winter load before it. It fed direct into a 33,000 volt overhead system extending for nearly 60 miles from the station, and connected by long underground cables to the overhead system of another company. Almost immediately after the machine was put to work, a quite extraordinary series of faults occurred on both the overhead lines and the cables, resulting, for a time, in almost daily surges up to short-circuit intensity, all of which it withstood without the least trouble. Its life was, indeed, an uneventful one of constant service until it was opened up for a full examination after three years' work, when it was found to be in perfect condition. So satisfactory, in fact, had been its behaviour that a second machine of the same capacity and voltage had already been ordered by the company. This machine was put into service in 1932.

The second high-tension machine embodied yet another notable advance in the design of turbo-alternators. The end-shields, instead of being constructed of cast-iron in the usual manner, were formed of a fibrous non-conducting and non-magnetic material, thus entirely preventing the eddy-currents due to the leakage flux. They also enhanced the quietness of the machine, as all tendency to vibration could be suppressed by attaching them to the studs holding the end-windings; a practice, of course, impossible with cast-iron end-shields. The lightness of the new end-shields was, moreover, a great convenience when examining the machine.

The next authorities to take advantage of the economies of generating current at the voltage required for transmission were

Fig. 6. Welded Mild Steel Stator Casing for 33,000 volt 3-phase Alternator of 25,000 kW. Carrying 523 Amps. at 0.8 P.F., 50 periods, 3,000 R.P.M.

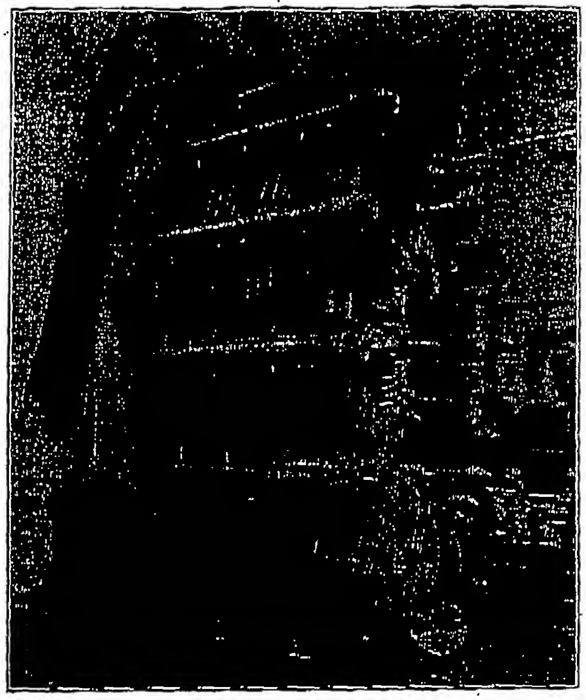


Fig. 7 Details of Windings of Stator at Exciter End on 33,000 volt alternator for 25,000 kW.

The Electricity Commissioners of South Africa, who, in March, 1932, ordered a high-voltage turbo-alternator for the Salt River power station at Cape Town. This was a unit of 20,000 kW capacity, also designed to operate normally at 33,000 volts. Their action was soon followed by that of the South Wales Electrical Power Distribution Co., who took advantage of the opportunity offered by the change of frequency of their system to replace an 11,000 volt alternator by one to generate at 33,000 volts.

So far every high-tension machine had been ordered for installation in an existing power station; but so fully had the economies of high-tension generation become appreciated that, on the advice of their consulting engineers, Messrs. Preece, Cardew and Rider, the Swansea Corporation decided to equip their new Tir John North Station with high-voltage machinery from the start. The size selected for the first units was 30,000 kW, and the station will commence operation with two machines of this capacity, delivering current at 33,000 to 36,000 volts.

The next standard transmission pressure is 66,000 volts. No machines have, as yet, been built for this pressure; but there is little doubt that the principle of the concentric conductor-bar has brought them within the bounds of possibility. Meanwhile the existence of reliable and efficient machines generating at 33,000 volts, enables a transmission pressure of 66,000 volts to be very economically obtained by their use in conjunction with auto-transformers. This combination would be both more efficient and less costly than the use of low-tension machines in conjunction with ordinary double-wound transformers.

Trolley Bus Development.

The trolley bus has many attractive features for urban transport—it does not suffer from the permanent way disability of the tramcar, it has fewer internal troubles than the petrol omnibus. Doubtless, as soon as economic conditions permit we shall see a large increase in trolley bus use; it will probably replace wholly or in part many tramway systems. The Walsall Corporation has, we note, just decided to increase its fleet of trolley buses with fifteen of the Sunbeam latest six-wheel type. These vehicles will be used on the Bloxwich route, at present served by tramcars. These railless vehicles will be fitted with regenerative electrical equipment manufactured by the British Thomson Houston Company and the double-deck bodies will each have seating accommodation for 60 passengers. It may also be noted that the Derby Corporation has lately placed a repeat order with Guy Motors for twelve more trolley buses. In this case the chassis will be equipped with the Guy 75 h.p. compound wound regenerative motor. The loaded weight of these buses is 10 tons, and, as with the 30 already in service, they are being fitted with the Westinghouse air brake.

TRAVELLING WAVES IN HIGH-VOLTAGE ALTERNATOR WINDINGS*

By E. FRIEDLÄNDER, Dr.-Ing.

(The paper was first received 13th August, 1940, and in revised form 7th June, 1941. The shortened version now published was received 26th March, 1942.)

SUMMARY

The security of the windings of an alternator generating at 22 kV or above and connected directly to a network depends mainly on the ability of the insulation to withstand surge voltages.

The distribution of surge voltages in the various types of stator winding hitherto adopted in commercial practice is examined, together with the relation of this distribution to that of the effective insulation available.

As alternators nearly always operate with the neutral point of the windings unearthed, the voltage stresses on the insulation near the neutral in these circumstances are determined and the danger of the use of graded insulation is discussed.

In no case does there appear to be an inherent tendency for all transient voltages to be distributed over the length of the stator winding in the same proportion as the generated voltage of the machine.

(1) INTRODUCTION

The windings of high-voltage alternators for direct connection to networks at operating voltages of 22 kV and above have hitherto been constructed according to one or other of the following methods:—

(a) The construction which has become standardized for machines at, say, 6·6 or 11 kV may be adapted merely by increasing the thickness of the insulation and preventing, as far as possible, the occurrence of concentrated stresses at critical points.

(b) The graded-layer winding, by which is meant one consisting of two or more single-layer sections of conventional design connected in series, the various sections being distributed over the same slots but having graded insulation.

(c) The concentric-conductor winding of Parsons and Rosen.[4] This has usually three sections in series, each of which generates one-third of the total voltage. The slots are round and the slot conductors are in the form of concentric tubes which are connected together at their ends by flat strips in the overhangs.

The insulation of all high-voltage gear is determined not so much by the normal operating voltage as by the need of security against transient surge voltages; the result is that the insulation is always ample for the service voltage and a fair comparison between different systems must be based upon knowledge of their behaviour under the most severe transient conditions.

The stresses due to surges in conventional windings have been investigated by various authors.[2, 3, 5, 6, 10, 12] Published information on the effect of surges on the concentric-conductor winding is very scanty. Various discussions that have taken place[13, 16, 17] were based largely on conceptions which, while they can be applied correctly to conventional windings, may not always be valid for the concentric-conductor winding.

The purpose of this investigation is to compare the relative efficiency of the insulation of the three types of winding with regard to their behaviour under surge stresses. As far as the conventional windings are concerned, most of the results may be quoted from published information. For the concentric-conductor winding, however, an extensive investigation had to be made; this necessarily constitutes a large part of the paper.

Theoretical studies of the type undertaken in this paper are bound to contain approximations, the validity of which can only be ascertained completely by means of appropriate tests. They should, however, contribute to a material clarification of the very complex processes in question.

(2) HIGH-VOLTAGE ALTERNATOR WINDINGS AND THEIR EQUIVALENT CIRCUITS

Figs. 1, 2 and 3 show typical slot designs for the three windings.

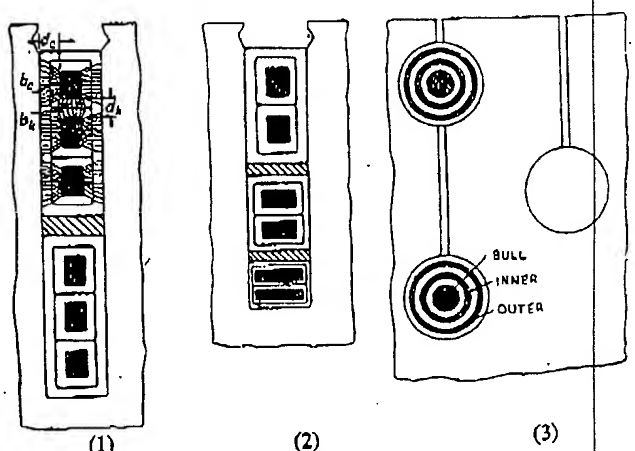


Fig. 1.—Slot of a conventional high-voltage alternator winding.
Fig. 2.—Slot of a multi-turn winding.
Fig. 3.—Slots of a concentric-conductor winding.

The conventional winding (Fig. 4a) may be considered as a chain of groups of coils, the turns of which have self-inductance as well as mutual inductance and also capacitance between one another and earth. The groups of coils are connected by the conductors in the overhang

* Communication from the Staff of the Research Laboratories of The General Electric Company, Ltd., England.
Written contributions are invited, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Contributions (except those from abroad) should reach the Secretary of The Institution not later than one month after publication of the paper to which they relate.

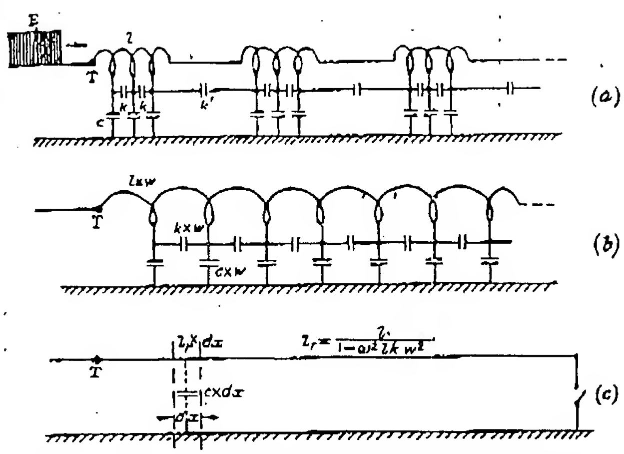


Fig. 4.—Equivalent circuit of the conventional winding.

which have considerably lower inductance and capacitance than those in the slots. It is known that the velocity of wave propagation in the overhang conductors may approach 10 times that in the slots,[6] so that it is possible to assume that the coil groups are connected directly together and thus arrive at one of the simplest equivalent circuits commonly used for alternator windings (Fig. 4*b*). Here the average inductance per unit length of conductor is replaced by concentrated inductances lw, which are shunted by interturn capacitances kw, where l and k are the inductance and capacitance per unit length of conductor and w is the length of conductor per turn. The capacitance to earth is likewise assumed to have a constant average value per unit length of conductor.

If all external wave-smoothing influences are neglected the amount of interturn insulation required in a conventional winding depends on the wave amplitude E_t to be expected at the alternator terminals and on the proportion of this voltage which the interturn capacitance (k in Fig. 4) is able to divert from the most highly exposed terminal turns. It has been shown experimentally by several investigators that the capacitances which couple electrically remote elements of the winding with one another may be neglected. Such capacitances are in general confined to the overhangs, and even when conductors of different phases are contained in the same slot the mutual coupling is weak.

The graded-layer winding may be treated as a series of uniform chains similar to those used for the conventional winding. As, however, the whole of each section of the winding lies at a given depth within the slots, the assumption of a constant average inductance per unit length is no longer correct. A perfectly satisfactory simplification, which at the same time facilitates analysis, does not seem to be possible. This investigation is therefore confined in the first place to a comparison between the limiting cases of the conventional winding and the concentric-conductor winding, between which the graded-layer winding appears as an intermediate stage.

The triple concentric-conductor winding is a system of three sections which are so tightly coupled magnetically and electrostatically that the phenomena of transient oscillations in the winding cannot be considered without introducing the mutual effect of each section on the others. The absence of interturn insulation in the usual sense (i.e. insulation between turns each of which is linked once only with the main flux of the alternator), together with the short turn length between electrically adjacent conductors (as distinct from those adjacent in space) make it permissible on the other hand to neglect the "k" capacitances between electrically adjacent conductors.

(3) VOLTAGE STRESSES DUE TO SURGES IN THE CONVENTIONAL WINDING

(3.1) General Scheme of Investigation

The transient phenomena to be observed in a circuit of the type shown in Fig. 4(*b*) are well known; it need only be recalled that when a rectangular wave enters the circuit at the terminal T, the maximum stress occurs in the end-turns at the very first moment.[8] Having regard to the accuracy which can be expected from investigations of this type it seems sufficient to calculate the initial voltage distribution from the chain of capacitances to earth and between adjacent conductors. No detailed investigation of the internal oscillations which accompany the transition from the initial to the final voltage distribution is given in this paper. Several have already been published[3, 8] but do not concern us here, as the knowledge of the initial voltage distribution is sufficient to determine the maximum thickness required for the interturn insulation. We may assume this insulation to be applied uniformly, as the initial stress to which the terminal turn can be subjected at the same time defines a limit which is unlikely to be exceeded in any part of the winding in the course of the subsequent oscillations.

(3.2) Surge Impedance and Wave Velocity

The surge impedance Z_w of the winding may be derived similarly to that of a smooth transmission line (Fig. 4*c*) by introducing an equivalent inductance per unit length, l_r, which results from the parallel connection of l and k and is, therefore, a function of the frequency ω according to the expression

$$l_r = \frac{l}{1 - \omega^2 lkw^2} \quad . \quad . \quad . \quad . \quad (1)$$

The introduction of this derived inductance into the usual line equations gives the surge impedance

$$Z_w = \sqrt{\frac{l_r}{c}} = \sqrt{\left[\frac{l}{c(1 - \omega^2 lkw^2)}\right]} \quad . \quad . \quad (2)$$

and similarly the wave velocity

$$v = \frac{1}{\sqrt{(l_r c)}} = \sqrt{\left(\frac{1 - \omega^2 lkw^2}{lc}\right)} \quad . \quad . \quad (3)$$

These equations are the same as those derived more rigorously by several authors.[8, 18] Z_w and v are functions of the frequency ω. For all frequencies which are sufficiently below the critical frequency $\omega_0 = 1/[w \times \sqrt{(lk)}]$ Z_w and v can be approximated by neglecting the cross capacitances k. On this assumption Z_w is known if a suitable value can be found for the inductance per unit length l, and c may be calculated from the slot dimensions.

(3.3) Inductance per Unit Length of Conductor

The exact calculation of the inductance l in the equations for travelling waves in windings appears to be one of the

weakest points in all the existing theories. From an examination of the conditions governing the design of large alternators, it is possible to arrive at the following conclusions:—

(a) Whatever the type of construction the inductance per unit conductor length (l) may be assumed to be a fairly constant percentage of that corresponding to the total sub-transient reactance of the alternator divided by the total conductor length.

This assumption will be shown later to apply only to those inductances in a concentric-conductor alternator winding which are due to fluxes in the iron core.

(b) The sub-transient reactance of any machine is fixed by considerations of security against short-circuits and is thus independent of the type of winding.

(c) For a given speed, service voltage and kVA capacity the e.m.f. induced per unit length of conductor is independent of the type of winding. The total conductor length, therefore, does not vary greatly between one type of winding and another.

From these three conclusions, it follows that the inductance l per unit of conductor length is about the same for any of the machines to be compared. Comparison between test results and observed and calculated wave velocities leads to the conclusion that for the purpose of this investigation the value of l may be taken as roughly 20×10^{-8} H per cm.

(3.4) Stresses in the End Turns due to the Initial Voltage Distribution

The maximum voltage e_t across the terminal turn insulation caused by a given rectangular terminal voltage E_t has been derived by several authors[1, 2, 3, 8, 9] from a difference equation which is valid for the capacitances per turn shown in Fig. 4(b); this may be simplified as shown in Appendix (10.1) to the following result:—

$$\frac{e_t}{E_t} = \frac{2}{1 + \sqrt{[(4k/c) + 1]}} \quad . \quad . \quad . \quad (4)$$

This equation gives a good approximation both for alternator and transformer windings and does not require the use of hyperbolic functions.

Numerical values may now be obtained from these equations, using the slot dimensions of Fig. 1. The values of c and k follow from the proportions of the slot without knowledge of the actual dimensions by using the formula for the plate condenser:—

$$C = \frac{\kappa}{36\pi} \times \frac{A}{d} \times 10^{-11}\mathrm{F} = 0\cdot0885 \times \kappa \times \frac{A}{d} \times 10^{-12}\,\mathrm{F} \quad (5)$$

Here A is the average area of each of the condenser plates in cm² and d the distance (cm.) between them; the permittivity of the insulating material is κ. Since the capacitance per unit length of conductor is required, A must be replaced by

$$A_c = \alpha_c \times L \times 2b_c \quad \text{or} \quad A_k = \alpha_k \times L \times b_k \quad . \quad (6)$$

where α_c and α_k are the proportions of the conductor length contributing to the capacitances and b_c and b_k are the effective widths, including fringing, of the condensers formed by the conductor and the earthed slot surface and by the opposing faces of the conductors respectively (Fig. 1). For the earth capacitance $\alpha_c = \lambda$, while for the interturn capacitance $\alpha_k = 1$. That is, adjacent conductors are assumed to have the same spacing in the slots as in the overhang. The thickness of the major insulation is d_c; b_k and d_k refer to the interturn capacitances.

From this:—

$$c = 0\cdot0885 \times \kappa \times \lambda \times \frac{2b_c}{d_c} \times 10^{-12}\ \mathrm{F\ per\ cm.} \quad (7)$$

and $$k = 0\cdot0885 \times \kappa \times \frac{b_k}{d_k} \times 10^{-12}\ \mathrm{F\ per\ cm.} \quad . \quad (8)$$

$$\frac{e_t}{E} = \frac{2}{1 + \sqrt{[(2d_c b_k)/(\lambda d_k b_c) + 1]}} \quad . \quad . \quad . \quad (9)$$

Introducing the proportions shown in Fig. 1 and taking $\lambda = 0\cdot4$ and $\kappa = 3\cdot5$

$$c = 0\cdot594 \times 10^{-12}\ \mathrm{F\ per\ cm.}$$
$$k = 0\cdot363 \times 10^{-12}\ \mathrm{F\ per\ cm.}$$

This gives

$$Z_w = \sqrt{\left(\frac{20 \times 10^{-8}}{0\cdot594 \times 10^{-12}}\right)} = 580\ \mathrm{ohms}$$

$$v = \frac{1}{\sqrt{(20 \times 10^{-8} \times 0\cdot594 \times 10^{-12})}}$$
$$= 29 \times 10^{8}\ \mathrm{cm./sec.} = 29\ \mathrm{m.\ per\ microsec.}$$

and $$\frac{e_t}{E_t} = 0\cdot70$$

It would therefore be sufficient if the interturn insulation had about 70 % of the thickness of the major insulation. By making the two thicknesses equal, a margin is provided for possible increased internal amplitudes due, for example, to chopped waves.

The necessary thickness of the major insulation depends on whether or not the neutral is earthed. If it is not, allowance must be made for reflection of the waves at the open end. This results in the whole winding attaining a voltage above earth equal to twice that of the incident wave, i.e. equal to $2E$. If the surge impedance Z_w of the winding is larger than that (Z_l) of the feeder this condition occurs only if the incident wave has a long tail and then after repeated reflections; if $Z_w = Z_l$ it occurs after the first reflection, while if $Z_w > Z_l$ the voltage may rise during a short time to a value

$$4E/(1 + Z_l/Z_w) \quad . \quad . \quad . \quad . \quad (10)$$

The consequent increased stress on the major insulation is shared by the interturn insulation, and it is agreed by all investigators that an unearthed neutral is always a highly stressed part of the winding.[5, 6, 10, 12] The most dangerous reflection occurs approximately $T_k = L/v$ sec. after the wave first strikes the winding. Assuming that the conductor length per phase is about 750 m. and v is about 29 m./microsec., then T_k is approximately 26 microsec., a time shorter than the average duration of dangerous surge waves.

In the absence of precautions to prevent the penetration of surge voltages into the winding it would be very dangerous to operate a conventional type of alternator with its

neutral unearthed if the thickness of the insulation were graded down towards the neutral. On the other hand a fully-insulated winding would be quite safe provided its insulation were properly co-ordinated with the line insulation.

(4) VOLTAGE STRESSES DUE TO SURGES IN CONCENTRIC CONDUCTOR WINDINGS

(4.1) General Scheme of Investigation

A power-frequency current entering at one of the terminals of a concentric conductor winding passes first, in series, through all the bull conductors of the phase; the end of the last conductor of the bull section is connected to the beginning of the inner section, the conductors of which surround those of the bull section. The current then passes through the inner section, flowing in turn through the outer section which surrounds both inner and bull sections.

As all the capacitances (k) between conductors in different slots may be neglected, it follows from Appendix (8.2) that each phase of the winding may be treated as if it were a triple-concentric cable, connected to form a three-turn loop as shown in Fig. 5. The length of

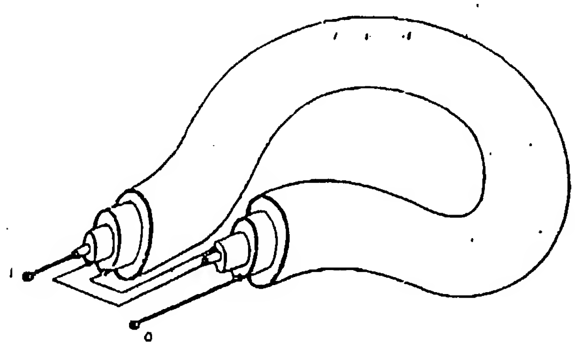


Fig. 5.—Triple-concentric conductor cable equivalent to a concentric-conductor winding.

the cable forming the loop would be one-third of the total conductor length per phase of the alternator, and each turn of the coil would correspond to one section of the winding.

The distribution of the equivalent reactances and capacitances per unit conductor length is shown in Fig. 6, in

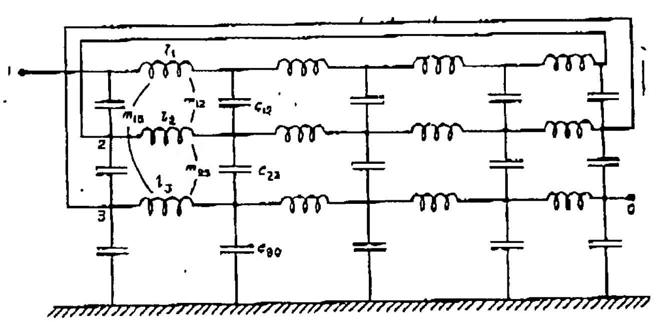


Fig. 6.—Simplified equivalent circuit of a concentric-conductor winding.

which 1 denotes the terminal, 2 the connection between bull and inner, 3 the connection between inner and outer, and 0 is the neutral. The suffixes 1, 2, 3 and 0 refer respectively to the bull, inner and outer conductors and the earthed metal of the slot wall.

It is shown in Appendix (8.2) that a travelling wave E striking the winding at the terminal 1 is split up into numerous secondary waves which, having due regard to the relative inductances of different parts of the winding, may be reduced to the internal waves, e_{f12}, e_{r21}, e_{f23}, e_{r32}, e_{f30} and e_{r03} and the external waves E_r and E_f. These waves are shown in Fig. 7 and more in detail later in Fig. 9. In

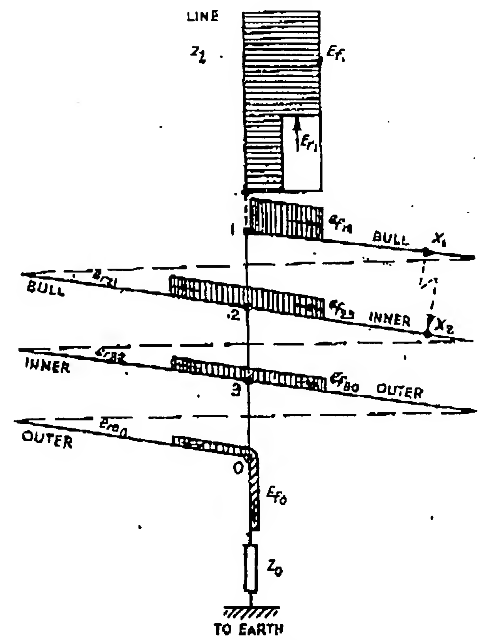


Fig. 7.—Initial distribution of voltage waves in a concentric-conductor winding.

Fig. 7 the winding is shown as a developed screw having three turns, the points of connection between the sections being shown at the middle of each turn. Voltage and current waves are distinguished by the suffix f for those travelling in the forward direction from the terminal to the neutral and by r for those travelling in the reverse direction.

The numbers in the suffix indicate the points of connection between which the wave travels; the first number indicates the point in the winding at which the wave in question is being investigated.

The assumptions on page 504 which lead to the postulation of a universal velocity of wave propagation in all windings are fully justified in the case of the triple-concentric conductor only if it is not embedded in iron.

Owing to the influence of the iron, two separate groups of waves occur which travel through the winding with different velocities. One group is bound only to fluxes and capacitances between the conductors, while the other is bound to the iron flux surrounding all the conductors.

The waves which are confined exclusively to the space between the conductors must have velocities nearly as high as those of waves in cables, whereas those that set up fluxes in the iron must be much slower on account of the high inductance. Each group of waves may be assumed to obey equations of the type derived for the cable, so that for each group it appears justifiable to assume that the waves which

travel along the different sections, all of which are of equal length, arrive simultaneously at their ends. Separate waves thus enter each conductor simultaneously and travel towards one another to meet at its mid-point. From this moment the waves are superimposed and the voltage stress on the insulation is correspondingly increased or decreased. The initial voltage distribution does not therefore necessarily give rise to the maximum interturn stress as is usually the case in the conventional winding.

(4.2) Surge Impedance and Wave Velocity

It is shown in Appendix (8.2), equation (33), that the slow wave velocity is given by

$$v = \frac{1}{\sqrt{(l_3 c_{30})}} \quad . \quad . \quad . \quad . \quad . \quad (11)$$

The inductance l_3 is that of the current loop between the outer conductor and earth and is the lowest of the inductances within the slot. If the total inductance per unit length were calculated from the inductance of the conductors in the slots l_3 would be found to be less than $\frac{1}{3}l$. The looser coupling between the conductors in the overhang accounts for some increase of the component inductances. No great error is therefore expected in putting $l_3 = \frac{1}{3}l$ and by using for l the same value as in the conventional winding. From the slot proportions shown in Fig. 3 and putting λ and κ as before it is found that $c_3 = 4 \cdot 63 \times 10^{-12}$ F/cm. and $v = 18$ m. per microsec. This value of the wave velocity is more than half the comparable velocity in the conventional winding. The surge impedance of the winding, which is the ratio between surge terminal voltage and surge current at the moment of impact of a rectangular wave, is given in equation (51) of Appendix (8.2). It may also be determined directly from the network of capacitances shown in Fig. 6. Suppose that c_w is the capacitance per unit conductor length between terminal and earth resulting from Fig. 6. Using published dimensions for a concentric-conductor alternator[4] and taking $\lambda = 0 \cdot 4$ as above $Z_w = 1/(vc_w) = 390$ ohms with earthed neutral and $Z_w = 403$ ohms with unearthed neutral. This is roughly two-thirds of the surge impedance of the comparable conventional alternator.

This surge impedance applies, however, to the slow waves only. For the fast waves v may be about 7 times as high as the velocity calculated above, and the corresponding surge impedance consequently may be about 1/7 of the former figure. The question arises to which one of these surge impedances the terminal voltage is due. The answer to this question may be attempted as follows. The surge impedance expresses the ability of the winding to take a more or less heavy current at the moment of wave impact. If first a winding with earthed neutral is considered it is seen that waves of the type shown in Fig. 7 are compatible even with the condition that the sum of the component current waves in the three conductors is zero. A high line current can flow because the earthed end makes it possible for the total charge to be moved to earth with the high velocity of the interconductor waves, in spite of the effect of the iron limiting the sum of the component current waves to nearly zero. From this it may be concluded that the high-velocity waves may cause a winding with earthed neutral to display a low surge impedance. When the neutral is insulated, however, no charge can flow to earth except across the stator iron: thus obviously the slow waves acquire a dominating influence corresponding to a higher value of surge impedance.

(4.3) Initial Voltage Distribution

The initial voltage distribution may be found in the usual way by assuming that all inductances are open-circuited at the instant of impact of the wave. As each wave is divided between the parallel paths starting at points 2 and 3 (Fig. 7) the terminal voltage is no longer sub-divided in the inverse ratio of the interturn capacitances. Even if all these capacitances were equal ($c_{12} = c_{23} = c_{30}$) the voltage between bull and inner would be 50 % of the terminal voltage. c_{12} is assumed here to be smaller than c_{23} and c_{30} so that the proportion of the total voltage appearing between bull and inner is still further increased. This stress distribution is, however, altered as soon as the waves e_{f12} and e_{r21}, as well as e_{f23} and e_{r32}, meet in the middle of the sections. The voltage between the two conductors is then

$$(e_{f12} + e_{r21}) - (e_{f23} + e_{r32}) = e_{f12} - e_{r32} \quad . \quad (12)$$

Using the numerical values given in Appendix (8.2), this equation shows that the insulation between the conductors is stressed by a voltage equal to 83·1 % of the terminal voltage. No influence of the iron has been taken into account in this figure. A calculation of the maximum voltage between adjacent conductors which is based on the assumption that the sum of the component current waves would be zero yields still 70 % of the terminal voltage. Introducing the surge impedance $Z_w = 67$ ohms, and assuming that $Z_l = 500$ ohms, the voltage between bull and inner is found to be 16 % of that of the incident wave E.

This seems to show that the winding with earthed neutral can be stressed by high voltages only if the surge impedance of the feeder is low. The possibility of the occurrence of relatively high stresses (about 70 %) cannot, however, be ruled out, e.g. in the limit case $Z_l = 0$, which it is usual to take as a basis for surge stress considerations. On this assumption the stresses between turns in the example of a conventional winding were 70 % of the terminal voltage. In the conventional winding, however, there is no difficulty in making the interturn insulation equal in strength to that between the conductor and earth. With the concentric winding this stress must be borne by insulation which has only one-third of the total thickness corresponding to the service voltage.

(4.4) Variation of Voltage Distribution with Time

(4.4.1) Application of Lattice Diagrams

Although the uncertainty introduced by some of the assumptions which it has been necessary to make detracts a little from the value of detailed information obtained by an extension of this investigation to subsequent reflections and refractions of the initial waves, such information is useful in showing the physical character of the phenomena.

The passage to and fro of the waves in the sections of the winding may most easily be followed by means of the lattice diagram due to Bewley.[7, 8] Suppose that in

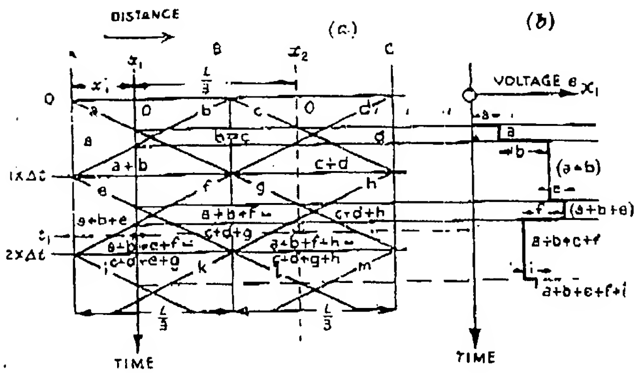


Fig. 8

(a) Method of constructing the lattice diagrams.
(b) Method of constructing the voltage-time diagrams for selected points of the lattice diagrams.

Fig. 8(a) distances in the winding are measured in the horizontal direction, while time is measured vertically downwards. A, B and C are points of connection between different sections at which waves moving over the winding are partially reflected and partially refracted. The oblique lines represent the movement of the wave fronts, the tangent of their angle with the horizontal being the wave velocity (distance/time). The sections are of equal length, and the wave velocity is constant so that the oblique lines continue to meet at equal time intervals, corresponding to the time of passage (Δt) of a wave over one section, however often the waves are reflected.

The amplitudes of the waves are shown by means of the letters "a," "b," "c," etc., on the oblique lines. Thus at the point B and at the time $1 \times \Delta t$ two waves "a" and "d" arrive. Each of these is partly reflected and partly refracted, so that two resultant waves emerge from B, one, "f," in the reverse direction made up of the reflected part of "a," and the refracted part of "d," and the other, "g," in the forward direction made up of the refracted part of "a" and the reflected part of "d."

If the incident, and therefore all the subsequent, waves have infinitely long tails, any point in the winding over which a wave has passed retains a voltage equal to the amplitude of that wave. Any subsequent waves add to or subtract from this voltage, so that the final voltage attained by any point of the winding is the algebraic sum of the individual increases or decreases due to the different waves.

Each of the lozenge-shaped spaces into which the diagram is divided by the oblique lines represents a collection of points in the length of the winding and in time, which have the same voltage. Consider a point the voltage of which is given by the voltage-time curve of Fig. 8(b), $e_{x_1}(t)$. In Fig. 8(a) this point is represented by the vertical line x_1. The voltage at x_1 is at first zero and remains so until the instant of the arrival of the wave "a," represented by the junction of x_1 and the oblique line "a." The voltage at x_1 then increases immediately to "a" and so remains until the line representing the reverse wave "b" cuts x_1, when the voltage is increased to (a + b), and so on.

This voltage (a + b) is thus that appertaining to any point in the conductor between A and B during a time interval which begins for each point when both the waves "a" and "b" have passed over it, and ends when either "e" or "f" passes over it, at which time the voltage is further increased to (a + b + e), or (a + b + f) as the case may be.

In the example of a diagram of this type shown in Fig. 10 only the figures in the spaces are given. The voltage step belonging to a given line is found from the difference between the voltages belonging to the adjacent spaces.

The difference between the voltages of two different points (x_1 and x_2 for instance) at a given time t_1, say, is the difference between the figures in the two lozenges in which lie the intersections of t_1 with x_1 and x_2. The distance between the points x_1 and x_2 in this example is equal to the section length $\frac{1}{3}L$. These points are thus separated in space only by the thickness of the insulation between the sections, so that the voltage governs the stress to which this insulation is subjected, as indicated by the arrow in Fig. 7.

(4.4.2) **Distribution of Transient Voltages.**

(4.4.2.1) *Neutral Earthed.*

Figs. 10 and 11 show the lattice diagram and the resulting voltage stresses in the winding under the assumption that the neutral is earthed ($Z_0 = 0$ in Fig. 7) and that the surge impedance of the line is negligible ($Z_l = 0$). The insulation stresses are evaluated for the points between "a" and "c," between "c" and "e" and between "e" and earth as shown at the top of Fig. 9. Each of these

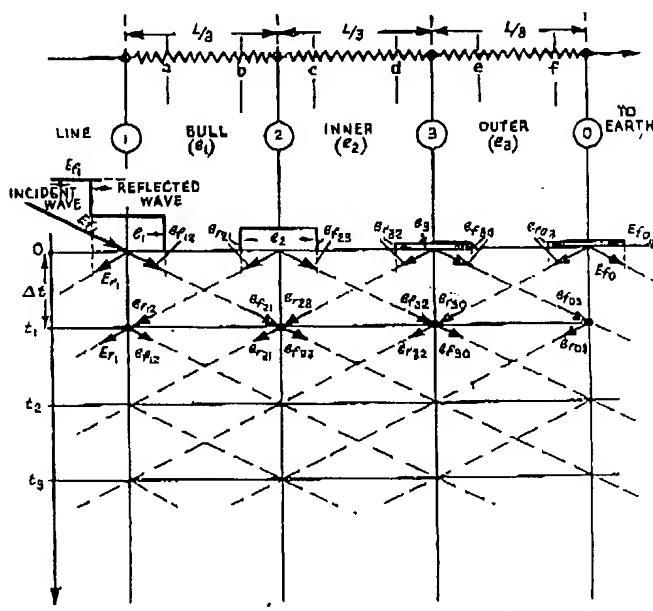


Fig. 9.—Construction of a lattice diagram for the concentric-conductor winding.

points is distant one-quarter of the section length from a point of connection, and all possible amplitudes between two adjacent sections must appear at some time between these points.

The initial wave amplitudes show that 60% of the voltage of the incident wave appears between bull and inner, as compared with the 33% which would correspond to the ideal distribution. After the first waves (e_{f12} and e_{r21} in Fig. 9) meet, this amplitude increases to 83%.

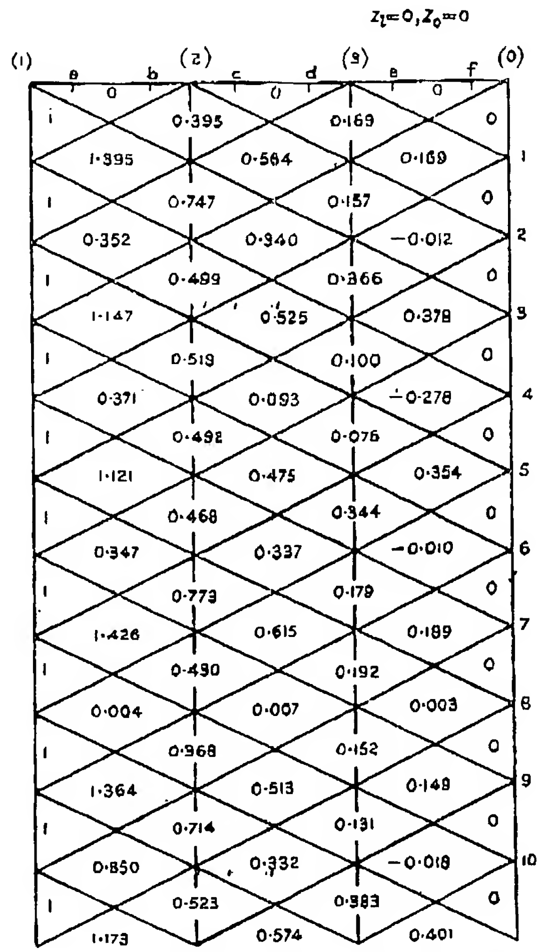


Fig. 10.—Lattice diagram for $Z_0 = 0$ (neutral earthed) and $Z_l = 0$ (surge impedance of the line negligible).

Fig. 12 shows the voltage oscillations for the case where $Z_l = Z_w$, including the relative terminal voltage e_1/e_{f12}. As no reflection occurs at the first instant the terminal voltage $e_1 = E_{f1}$ during the time Δt. At the end of this time, the wave from the point of connection 2 arrives at 1 and increases the terminal voltage by 66 %.

The voltage stresses between adjacent sections are about 85 % of the amplitude of the incident wave.

Fig. 13 is drawn for $Z_l = 9Z_w$ and $E_{f1} = 5e_{f12}$. Here the highest voltage between adjacent turns is about one-fifth of that of the incident wave. The terminal voltage still reaches half the voltage of the incident wave in spite of the high ratio Z_l/Z_w.

The distribution of the maximum voltage, however, becomes more uniform, the maximum voltage stress on the insulation approximating to one-third of the maximum terminal voltage. This provides a reason why experiments made with a surge generator of low capacity (one presenting a considerable series resistance to the winding under investigation) show a more uniform voltage distribution than that which may be expected under service conditions. The oscillogram shown in the *Journal* (1940, 86, p. 366) was apparently made with a generator of limited output. This may be gathered from the rapid diminution of the terminal voltage, which falls nearly to zero within 5 microsec.

These investigations thus point to the possibility that the different parts of the insulation of a concentric conductor winding with earthed neutral may be unequally stressed by surges, the bull insulation in this case carrying the greater part of the incident voltage. Further, even if the surge impedance of the winding is relatively low, the terminal voltage is soon increased above its initial moderate value by internal reflection of the incident waves.

(4.4.2.2) *Neutral Unearthed.*

It is known that windings operating with unearthed neutral may be very differently stressed according to whether the incident wave approaches the winding on one, two, or symmetrically on all three of the line conductors. The latter case is in general the most dangerous and the investigation is therefore confined to this condition in which the stresses may be found as above by assuming the surge impedance between neutral and earth to be infinite.

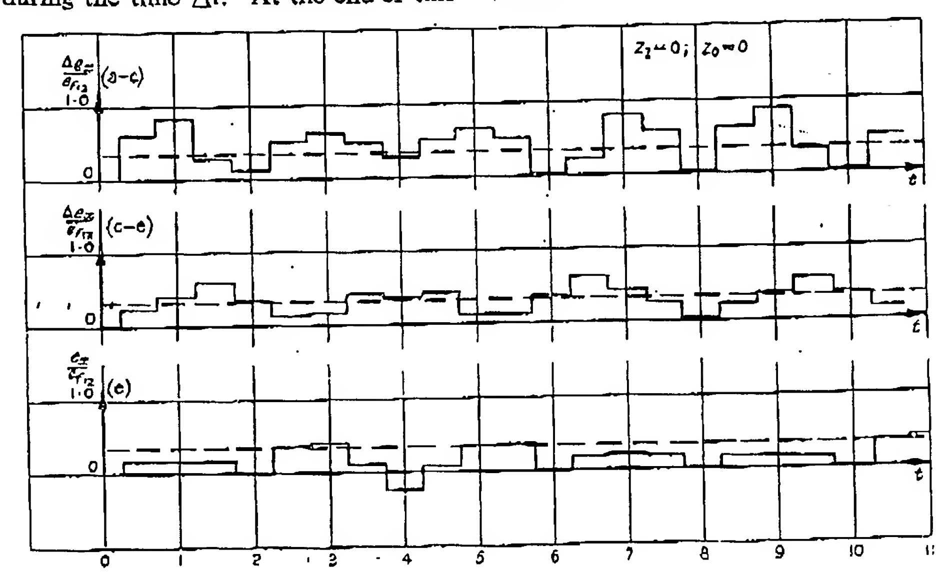


Fig. 11.—Voltage/time diagram derived from Fig. 10.

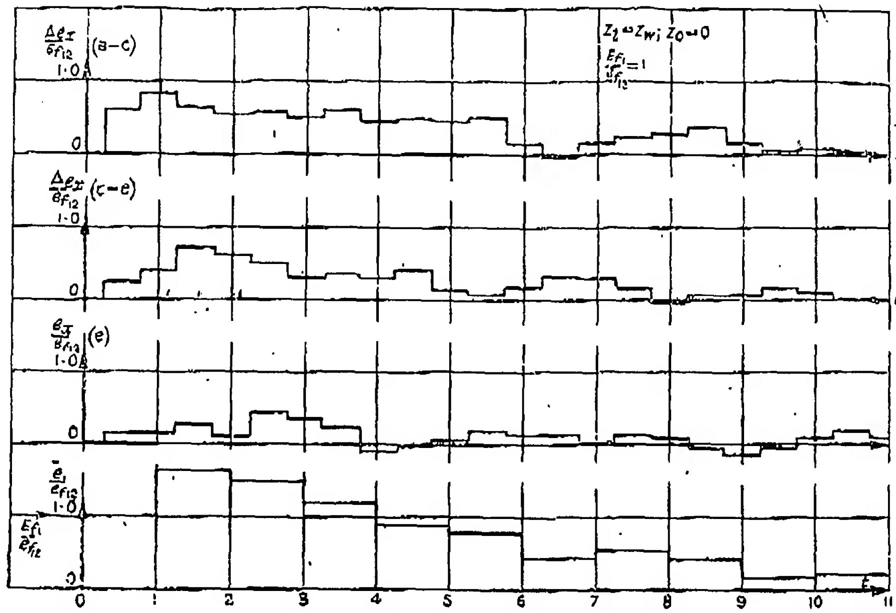


Fig. 12.—Voltage/time diagram for $Z_l = Z_w$.

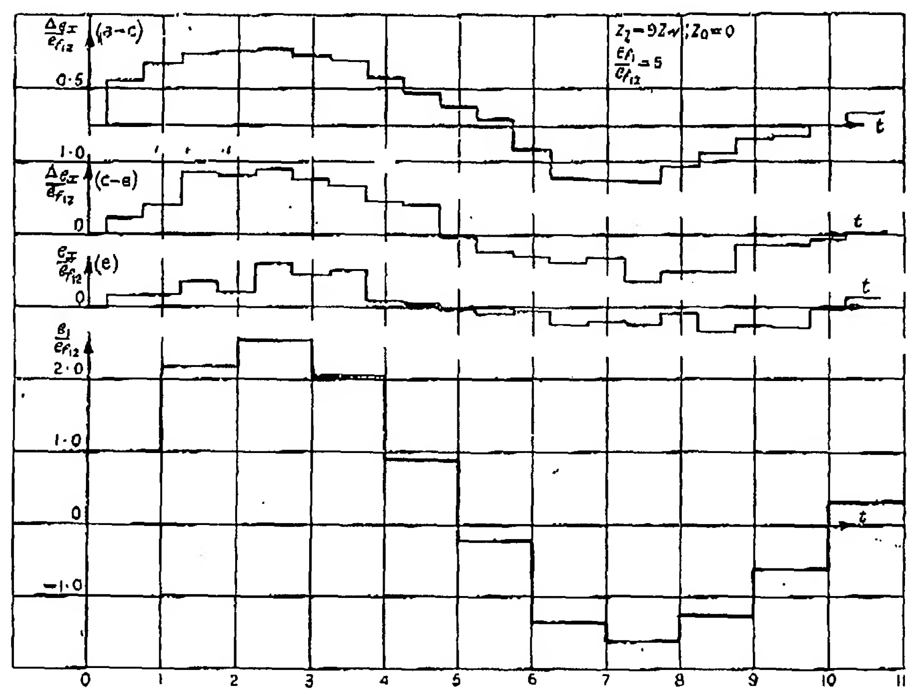


Fig. 13.—Voltage/time diagram for $Z_0 = 0$, $Z_l = 9Z_w$.

Fig. 14 shows the voltages in the limiting case where $Z_0 = \infty$, $Z_l = 0$, i.e. that of a 3-phase stroke near to the terminals. The voltage across the insulation between bull and inner (a-c) is shown in Fig. 14(*a*) and the neutral voltage e_0 in Fig. 14(*b*).

As the surge impedance of the line increases, the stresses between adjacent turns for a given value of E_{f1} decrease. The neutral, however, attains twice the voltage of the incident wave as shown in Fig. 15. This shows the voltages for different values of Z_l/Z_w; the amplitude of the incident wave E_{f1} being assumed to be such that the initial wave e_{f12} is always unity. The voltage e_{f12} occurring with $Z_l = 0$ may be supposed to originate from an incident wave of $0{\cdot}5e_{f12}$ as the incident wave is doubled by reflection when Z_l is negligible compared with Z_w. The wave necessary to excite the same terminal voltage is equal to unity with $Z_l = Z_w$, and to 2 with $Z_l = 3Z_w$.

The curves show that whatever the ratio between the

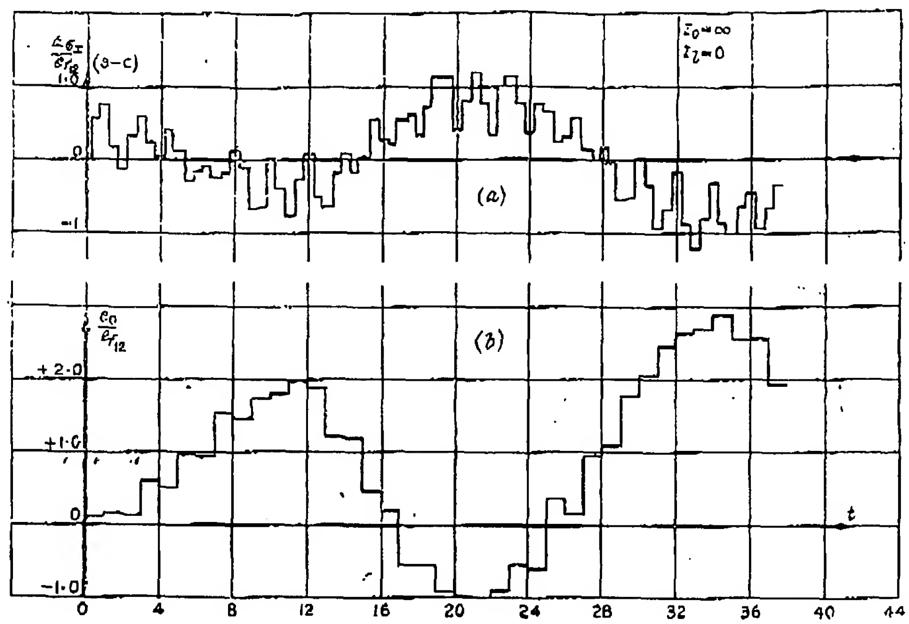


Fig. 14.—Voltage/time diagram for the bull and outer insulation with $Z_0 = \infty$ (unearthed neutral) and $Z_l = 0$.

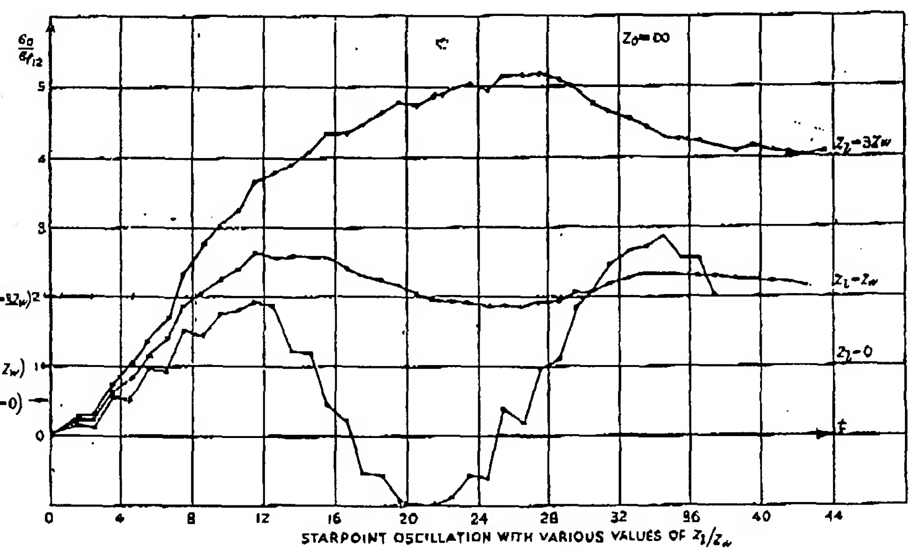


Fig. 15.—Voltage/time diagram for the outer insulation with unearthed neutral and various line surge impedances ($Z_l = 0, Z_w, 3Z_w$).

surge impedances of the line and of the winding, the neutral voltage may rise to a value of at least the amplitude of the incident wave in a fairly short time.

The time scale of the diagrams relating to an unearthed neutral may be calculated approximately from the wave velocity and the section length of the conductor; assuming this to be about 250 m. and the velocity to be $v = 18$ m. per microsec., we find the unit of time to be $250/18 = 14$ microsec. with, for example, $Z_l = Z_w$, the insulation between the outer and earth will have to support the full amplitude of the incident wave in about $5 \times 14 = 70$ microsec., which is well within the tail length of recorded surges. If the amplitude of the incident wave is only 100 kV—a very low value for a 33-kV network—the breakdown voltage of the outer insulation may well be reached.

This seems to prove that the fears expressed on several occasions[10, 17(disc.)] as to the possibility of the neutral of these windings acquiring dangerous voltages are justified; although surges of sufficient duration and amplitude to endanger such windings may be rare, their occurrence cannot be ruled out. If the insulation is graded down towards the neutral some kind of protection is obviously imperative.

(5) INFLUENCE OF THE FRONT LENGTH OF THE INCIDENT WAVE UPON THE DIFFERENT WINDINGS AND UPON METHODS OF PROTECTION

The probability of a breakdown depends on:—

(a) The state of the insulation.
(b) The amplitude of a voltage stressing the insulation.
(c) The duration of the voltage stress.

The insulation may be assumed to be uniform and of equal quality in the three cases. As the amplitude of the voltages has already been considered, it only remains to compare the durations.

So far as the ordinary winding is concerned, it is necessary to know how long the insulation may be exposed to a stress near the maximum which can occur. It therefore suffices to assume that the stress cannot last longer than the time taken by a wave front having the steepness found from the initial voltage distribution, to travel along its own length with the previously calculated speed v. Assuming that a voltage $0 \cdot 7E_t$ appears over a turn length w, the duration $T_w = (w/v) \times (1/0 \cdot 7)$. If $w = 17$ m. and $v = 29$ m. per microsec., $T_w = 0 \cdot 84$ microsec., while the maximum amplitude can last for only a fraction of this time. There is thus a high probability that the breakdown delay of the insulation will prevent breakdown in most cases.

If the front of the original wave is longer than T_w, then the maximum voltage calculated here is not reached at all. It is therefore possible to protect the interturn insulation of a conventional winding merely by increasing the front length of the incident wave to the order of, say, 2 microsec.; the stresses are thus reduced to less than half the amplitude calculated on the assumption of a rectangular wave. This makes it possible to protect the winding by comparatively cheap condensers or short lengths of cable connected in series or in parallel with the alternator, in accordance with many published suggestions.[8, 9, 10, 12]

Deep, narrow slots must always be used in high-voltage alternators, so that there is no difficulty in finding the small amount of additional space required for reinforced insulation and thus making the winding capable of withstanding any interturn stresses that may occur. In addition a large measure of protection is afforded by the electrostatic capacitance of the apparatus and lines connected to the incoming feeder at the power station.

Turning now to the concentric winding, Fig. 8(a) shows that if a very steep wave front is considered, the durations of stress given by the lattice diagrams are different in parts of the winding. The greatest duration occurs for one group of voltages in the central axis of Fig. 7. The other group has its maximum duration midway between two points of connection of the winding. The increasing probability of breakdown as the duration of the voltage stress increases would be sufficient to explain breakdowns due to travelling waves occurring either near the terminals, the neutral or the connections between the sections, or the middle point of a section. The same argument applies if a wave with a longer front is considered. From this it follows that the probability of the voltage reaching its maximum value is greatest for these critical points. Should the insulation be damaged repeatedly at one such point of an otherwise sound wiring, there is a great probability that travelling waves are the cause. The diagram given by Horsley* showing the points where damaged insulation was found on one of the 30 000-kW, 33-kV alternators in the Tir John power station, Swansea, namely in the middle of the outer conductor, thus indicates that travelling waves may have been responsible for the breakdown which drew attention to some weak spots.

The duration of surge voltages appearing at such critical points of the winding may approach Δt, the time taken by the wave to travel along one third of the total conductor length L, namely about 14 microsec. for the slow waves and about 2 microsec. for the fast ones. It follows that unless the wave front can be increased to more than these times no protection is provided for the interturn insulation.

(6) CONCLUSION

The interturn insulation of conventional alternator stator windings is stressed by voltages of about the same amplitude as those to be expected between the terminal turns of a graded-layer winding and between the conductors of a concentric-conductor winding if the surge impedance of the line is low. In the conventional winding, the thickness of the interturn insulation may easily be increased to a sufficient extent to withstand the consequent voltage stress by slightly increasing the depth of the relatively narrow slots. The danger due to such voltage stresses is minimized by their very limited duration (of the order of 1 microsec.). The maximum value of the stress may often be still further reduced at small cost by adding condensers at the machine terminals.

The concentric-conductor winding, which is designed on the assumption that the operating voltage is sub-divided equally between the three sections, may be stressed unequally by travelling waves, so that, whether or not the neutral is earthed, one-third of the total insulation may have to sustain 70 % or more of the terminal voltage. The duration of this stress is a multiple of that of the interturn stresses in conventional windings. The surge impedance of the winding is greatly reduced if its neutral is earthed, so that some reduction of the terminal voltage may result if the surge impedance of the line is high.

In the graded-layer winding dangerous stresses may occur in the end turns of the sections, on account of the passage of the wave from one winding to another of a higher surge impedance.

The voltages which may occur at the neutral of any type of winding operating with the neutral unearthed are such that it is unsafe to grade the insulation unless protection against excessive voltage is provided; the concentric-conductor winding is no exception to this rule. The voltages that are found to occur in the absence of such protection, in particular those between the outer conductor and earth, may explain some of the observed failures. While the relatively high capacitance to earth of the winding ensures that only a surge wave having a long tail can damage the insulation, the necessary length is such, however, as may be expected to occur in practice.

It follows that both the graded winding of conventional design and the concentric-conductor winding should be provided with some form of surge protection, such as surge arresters disposed along the length of the winding in accordance with the distribution of the insulation, so as

* *Journal I.E.E.*, 1940, 86, p. 345, Fig. 4.

to ensure that surge voltages are distributed in the same proportions as the generated e.m.f.

Uniform distribution of surge voltages does not occur automatically in any known type of alternator winding, even if the neutral is earthed. At a given time only a very small proportion of machines are run with earthed neutral. On the other hand, the extent to which protection can be obtained by surge arresters connected to the neutral point is limited by the conditions during the existence of an earth fault in the network, when the alternator neutral rises to a voltage above earth equal to its phase-to-earth voltage.

The problem of the design of an alternator to generate directly at 22 kV or 33 kV, or at higher voltages, appears to be best solved by avoiding graded insulation and applying the conventional methods of construction hitherto used for 6·6 or 11 kV, the insulation being increased in thickness to carry the increased voltage. Such conventional windings have great inherent security against transient surge voltages, which affect chiefly the interturn insulation, and their major insulation may be easily and cheaply protected against more sustained over-voltages by means of surge arresters preferably applied both to the terminals and to the neutral if this is unearthed.

These conclusions have arisen from theoretical considerations based on a number of approximations. For obvious reasons it has not been possible to check a number of them by experiment, although such a check would of course be desirable.* Any experimental work may, however, be subject to considerable errors due to the depth of penetration of the flux into the iron of the core varying with the current in the conductors. The actual wave shapes found experimentally with low currents thus might not agree with the theoretical results, which are based on conditions that probably are better approached with heavy surge currents. The results obtained lend no support to earlier investigators,[13, 16, 17] who claim to have shown that the distribution of the capacitances in the concentric-winding conductor would give even distribution of surge stresses over its different sections.

Acknowledgments

The author is indebted to Dr. C. C. Garrard for having suggested this investigation, to Dr. M. Kahn and Mr. J. W. Howard for the opportunity of useful discussions, and to Mr. C. J. O. Garrard for the great help he has given in the presentation of the paper.

(7) BIBLIOGRAPHY

(1) R. RÜDENBERG: *Elektrotechnische Zeitschrift*, 1914, **35**, p. 412.
(2) K. W. WAGNER: *Elektrotechnik und Maschinenbau*, 1915, 33, pp. 89 and 105.
(3) L. F. BLUME and A. BOYAJIAN: *Transactions of the American I.E.E.*, 1919, 38, p. 577.
(4) C. A. PARSONS and J. ROSEN: *Journal I.E.E.*, 1929, **67**, p. 1065.
(5) F. D. FIELDER and E. BECK: *Transactions of the American I.E.E.*, 1930, **49**, p. 1577.
(6) E. W. BOEHNE: *ibid.*, 1930, **49**, p. 1587.
(7) L. V. BEWLEY: *Transactions of the American I.E.E.*, 1931, **50**, p. 1215.
(8) L. V. BEWLEY: "Travelling Waves on Transmission Systems" (New York, 1933).
(9) R. RÜDENBERG: "Elektrische Schaltvorgänge" (1933), 3rd edition.
(10) J. F. CALVERT: *Transactions of the American I.E.E.*, 1934, **53**, p. 139.
(11) E. M. HUNTER: *ibid.*, 1935, **54**, p. 599.
(12) H. NEUHAUS and R. STRIGEL: *Archiv für Elektrotechnik*, 1935, **29**, p. 702.
(13) J. ROSEN: *Compte Rendu, Conférence Internationale des Grands Réseaux Électriques à Haute Tension*, 1937, **1**, p. D11.
(14) L. GOSLAND: Contribution to the discussion on a paper by Messrs. H. TRENCHAM and K. J. R. WILKINSON, *Journal I.E.E.*, 1937, **80**, p. 470.
(15) R. ELSNER: *Wissenschaftliche Veröffentlichungen aus den Siemenswerken*, 1939, **18**, p. 1.
(16) Discussion on a paper by F. W. LAWTON, *Journal I.E.E.*, 1939, **85**, pp. 503–513.
(17) W. D. HORSLEY: *Journal I.E.E.*, 1940, **86**, p. 345.
(18) R. RÜDENBERG: *Transactions of the American I.E.E.*, 1940, **59**, p. 1031; also discussion, p. 1257.
(19) R. RÜDENBERG: *Journal of Applied Physics*, 1940, **11**, p. 665.

(8) APPENDICES

(8.1) Derivation of Equation (4). The Voltage across the End Turn of the Winding

The voltage to earth of the nth element of a chain of capacitances consisting of a finite number, N, of series elements each having a capacitance kw and the same number of shunt elements each having a capacitance to earth of cw is:—

$$e_n = \frac{\sinh (N-n)\alpha}{\sinh N\alpha} E_t \quad . \quad . \quad . \quad (13)$$

if the Nth element is earthed and

$$e_n = \frac{\cosh (N-n)\alpha}{\cosh N\alpha} E_t \quad . \quad . \quad . \quad (14)$$

if the Nth element is unearthed.[1, 2, 9] E_t is the terminal voltage ($n = 0$). The term α in these equations is given by

$$\sinh \frac{\alpha}{2} = \frac{1}{2}\left(\epsilon^{\frac{\alpha}{2}} - \epsilon^{-\frac{\alpha}{2}}\right) = \frac{1}{2}\sqrt{\frac{c}{k}} \quad . \quad . \quad (15)$$

The voltage across the end member of such a chain, i.e. between $n = 0$ and $n = 1$, is

$$e_t = e_0 - e_1 = \left[1 - \frac{\sinh (N-1)\alpha}{\sinh N\alpha}\right] E_t \quad . \quad (16)$$

when the end of the chain is earthed, and

$$e_t = \left[1 - \frac{\cosh (N-1)\alpha}{\cosh N\alpha}\right] E_t \quad . \quad . \quad . \quad (17)$$

if the end is unearthed.

If, as in nearly all practical cases, $N\alpha$ is larger than 4, equations (16) and (17) lead to the same approximation:—

$$e_t = E_t(1 - \epsilon^{-\alpha}) \quad . \quad . \quad . \quad . \quad (18)$$

* Since this paper was written, Messrs. J. S. Cliff and H. F. Jones have investigated the voltage oscillations in a threefold concentric conductor of the type shown in Fig. 5, by means of the recurrent-surge oscillograph. The results obtained are in good agreement with those predicted by the theory.

The combination of (18) and (15) gives

$$e_r = E_r\epsilon^{-\frac{\alpha}{2}} \times \sqrt{\frac{c}{k}} \quad . \quad . \quad . \quad . \quad (19)$$

Introducing $\epsilon^{-\frac{\alpha}{2}}$ by re-writing equation (15)

$$\left(\epsilon^{-\frac{\alpha}{2}}\right)^2 + \sqrt{\frac{c}{k}} \times \epsilon^{-\frac{\alpha}{2}} = 1$$

from which

$$\epsilon^{-\frac{\alpha}{2}} = \sqrt{\left(1 + \frac{c}{4k}\right)} - \frac{1}{2}\sqrt{\frac{c}{k}} \quad . \quad . \quad (20)$$

From this and equation (19) the equation (4) on page 494 is obtained.

(8.2) Calculation of the Transient Voltage Distribution

(8.2.1) Symbols and fundamental differential equations.

Fig. 6 shows the distribution of the inter-conductor capacitances per unit length, c_{12}, c_{23} and c_{30}.

It is implied that there are no capacitances other than those between adjacent conductors. The self-inductances per unit length of the three conductors are l_1, l_2 and l_3, and the mutual inductances, m_{12}, m_{23} and m_{13}. With the length of the line x as variable, the differential equations are:—

$$\left.\begin{aligned}
\frac{\partial i_1}{\partial x} &= -c_{12}\frac{\partial(e_1 - e_2)}{\partial t} \\
\frac{\partial i_2}{\partial x} &= -c_{23}\frac{\partial(e_2 - e_3)}{\partial t} + c_{12}\frac{\partial(e_1 - e_2)}{\partial t} \\
\frac{\partial i_3}{\partial x} &= -c_{30}\frac{\partial e_3}{\partial t} + c_{23}\frac{\partial(e_2 - e_3)}{\partial t} \\
\frac{\partial e_1}{\partial x} &= -l_1\frac{\partial i_1}{\partial t} - m_{12}\frac{\partial i_2}{\partial t} - m_{13}\frac{\partial i_3}{\partial t} \\
\frac{\partial e_2}{\partial x} &= -m_{12}\frac{\partial i_1}{\partial t} - l_2\frac{\partial i_2}{\partial t} - m_{23}\frac{\partial i_3}{\partial t} \\
\frac{\partial e_3}{\partial x} &= -m_{13}\frac{\partial i_1}{\partial t} - m_{23}\frac{\partial i_2}{\partial t} - l_3\frac{\partial i_3}{\partial t}
\end{aligned}\right\} \quad . \quad (21)$$

The resulting voltages and currents are composed of exponential functions of the form

$$e = A \times \epsilon^{ax} \times \epsilon^{pt} \quad . \quad . \quad . \quad . \quad (22)$$

so that
$$\frac{\partial e}{\partial x} = a \times A \times \epsilon^{ax} \times \epsilon^{pt} = ae$$

$$\frac{\partial e}{\partial t} = p \times A \times \epsilon^{ax} \times \epsilon^{pt} = pe$$

from which follow the operational symbols:—

$\frac{\partial}{\partial x} = a$ for the length derivative, and

$\frac{\partial}{\partial t} = p$ for the time derivative

Since the amplitude of an undamped wave travelling along a smooth line is constant

$$de = \frac{\partial e}{\partial x}dx + \frac{\partial e}{\partial t}dt = 0$$

from which is obtained the wave velocity

$$v = \frac{dx}{dt} = -\frac{p}{a} \quad . \quad . \quad . \quad . \quad . \quad (23)$$

The equations (21) may be rewritten by introducing (23), giving

$$e_1 = v \times (l_1 i_1 + m_{12}i_2 + m_{13}i_3) \quad . \quad . \quad . \quad (24)$$

$$e_2 = v \times (m_{12}i_1 + l_2 i_2 + m_{23}i_3) \quad . \quad . \quad . \quad (25)$$

$$e_3 = v \times (m_{13}i_1 + m_{23}i_2 + l_3 i_3) \quad . \quad . \quad . \quad (26)$$

$$i_1 = v \times c_{12}(e_1 - e_2) \quad . \quad . \quad . \quad . \quad . \quad . \quad (27)$$

$$i_2 = v \times [c_{23}(e_2 - e_3) + c_{12}(e_2 - e_1)] \quad . \quad (28)$$

$$i_3 = v \times [c_{30}e_3 + c_{23}(e_3 - e_2)] \quad . \quad . \quad . \quad (29)$$

The elimination of the currents and voltages from these equations leads to a cubic equation for v, and thus yields three different wave velocities. That is, in the general case, three different waves appear, each having a different velocity. However, by taking into account the conditions governing the mutual and self-inductances, which are shown by Fig. 25, the problem may be much simplified. The magnitude of the inductances is determined by the assumption that the slot walls act as the return conductor. It is well known that no magnetic field can be built up inside a tubular conductor by currents whose sum is zero, flowing in concentric tubes surrounding the inner tube. Further, no perceptible magnetic field can exist inside the copper of the conductor itself, owing to the skin effect consequent upon the high-frequency components of surge waves. The solid copper contributes only to the damping by the eddy currents surrounding the wave front. Thus the magnetic field with which any inner conductor is interlinked if one of the other conductors nearer the slot surface carries a current must be the same as the field with which the current carrying conductor is itself interlinked. Conversely, if one of the inner conductors carries a current, the field produced is not entirely interlinked with the outer conductors.

The portion embraced by the outer conductor, however, is the same as if the field had been produced by the same current flowing in this outer conductor instead of in the inner one. This statement is true generally and does not apply only to a concentric cable. It holds good, for instance, for the windings of a concentric transformer if the field inside the conductors is negligible in comparison with the field in the space between the conductors. It is therefore possible to introduce the following relations, which apply approximately also to the overhang:—

$$\left.\begin{aligned} m_{12} &\simeq l_2 \\ m_{12} \simeq m_{23} &\simeq l_3 \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad (30)$$

Equation (26) may now be rewritten

$$e_3 = v_3 l_3(i_1 + i_2 + i_3) \quad . \quad . \quad . \quad . \quad (31)$$

Adding equations (27), (28) and (29) we obtain

$$i_1 + i_2 + i_3 = v_3 \times c_{30} \times e_3 \quad . \quad . \quad (32)$$

from which

$$v_3 = \pm\sqrt{\left(\frac{1}{c_{30}l_3}\right)} \quad . \quad . \quad . \quad . \quad (33)$$

A second velocity may be obtained from (25), (26), (27), (28) and (30). Thus

$$i_1 + i_2 = v_2 \times c_{23}(e_2 - e_3) \quad . \quad . \quad . \quad (34)$$

$$e_2 - e_3 = v_2(l_2 - l_3) \times (i_1 + i_2) \quad . \quad . \quad (35)$$

From which

$$v_2 = \pm\sqrt{\left[\frac{1}{c_{23}(l_2 - l_3)}\right]} \quad . \quad . \quad . \quad (36)$$

A third velocity follows from (24) and (25) with (27). Thus

$$e_1 - e_2 = v_1 \times (l_1 - l_2) \times i_1 \quad . \quad . \quad (37)$$

$$v_1 = \pm\sqrt{\left[\frac{1}{c_{12}(l_1 - l_2)}\right]} \quad . \quad . \quad . \quad (38)$$

The velocities v_1, v_2 and v_3 reduce to a common velocity if the presence of iron is neglected. The following investigation is based upon this assumption.

The existence of a single common velocity in all the conductors means that the winding behaves like a number of transmission lines interlinked by mutual surge impedances[9] and that a pair of waves travelling in the forward and reverse directions must be impressed on each of the conductors wherever a surge voltage appears in any one of them. The following surge impedances may thus be introduced:—

$$\left.\begin{aligned} Z_1 &= vl_1 \\ Z_2 &= vl_2 \\ Z_3 &= vl_3 \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad (39)$$

$$\left.\begin{aligned} Z_{12} &= Z_1 - Z_2 = \frac{1}{vc_{12}} \\ Z_{23} &= Z_2 - Z_3 = \frac{1}{vc_{23}} \\ Z_{13} &= Z_1 - Z_3 = \frac{1}{v}\left(\frac{1}{c_{12}} + \frac{1}{c_{23}}\right) \end{aligned}\right\} \quad . \quad . \quad (40)$$

(8.2.2) **Calculation of the initial wave distribution in the triple-concentric conductor.**

All currents and voltages obey equations analogous to (24) to (29). The end of the first section is connected to the beginning of the second, and the end of the second to the beginning of the third, so that

$$e_{r21} = e_{f23}, \quad e_{r32} = e_{f30} \quad . \quad . \quad . \quad (41)$$

The symbols have the meaning indicated in Fig. 7. As the resultant current in each of these connections is zero the amplitudes of the waves travelling in opposite direction are likewise equal, so that

$$i_{r21} = -\,i_{f23}, \quad i_{r32} = -\,i_{f30} \quad . \quad . \quad . \quad (42)$$

The terminal voltage $e_1 = e_{f12}$ depends on the surge impedance Z_l of the line upon which the wave originates and on its original amplitude E_{f1}. The voltage at the terminal may be calculated by the well-known laws of wave reflection:—

$$e_1 = e_{f12} = 2E_{f1} - i_{f12}Z_l \quad . \quad . \quad . \quad (43)$$

Similarly, the voltage e_0 at the neutral is

$$e_0 = e_{r03} = i_0 Z_0 \quad . \quad . \quad . \quad . \quad (44)$$

Z_0 is the surge impedance between neutral and earth. The distribution of the incident wave may now be calculated from equations (24)–(26) with (30), and (39)–(44). The forward waves are

$$2E_{f1} - Z_l i_{f12} = Z_1 i_{f12} + Z_2 i_{f23} + Z_3 i_{f30} = e_{f12} \quad (45)$$

$$\alpha_2 e_{f12} = Z_2(i_{f12} + i_{f23}) + Z_3 i_{f30} = e_{f23} \quad (46)$$

$$\alpha_3 e_{f12} = Z_3(i_{f12} + i_{f23} + i_{f30}) = e_{f30} \quad . \quad (47)$$

While the reverse waves are

$$Z_1 i_{r21} + Z_2 i_{r32} + Z_3 i_{r03} = -\,e_{r21} \quad . \quad . \quad (48)$$

$$Z_2(i_{r21} + i_{r32}) + Z_3 i_{r03} = -\,e_{r32} \quad . \quad . \quad (49)$$

$$Z_3(i_{r21} + i_{r32} + i_{r03}) = -\,e_{r03} \quad . \quad . \quad (50)$$

The solution of these equations gives the effective terminal surge impedance:—

$$Z_w = \frac{e_{f12}}{i_{f12}} = Z_1 - \frac{Z_{23}^2}{Z_{13}} - \frac{Z_3^2}{Z_2 + \dfrac{Z_0 Z_3}{Z_0 + Z_3}} \quad . \quad (51)$$

with which the terminal wave follows as usual from

$$\frac{e_{f12}}{E_{f1}} = \frac{2}{1 + \dfrac{Z_l}{Z_w}} \quad . \quad . \quad . \quad . \quad . \quad (52)$$

The internal waves derived from equations (45–50) may be expressed by the ratios

$$\alpha_2 = \frac{e_{f23}}{e_{f12}} = 1 - \frac{Z_{12}}{Z_w} \quad . \quad . \quad . \quad . \quad (53)$$

$$\alpha_3 = \frac{e_{f30}}{e_{f12}} = 1 - \frac{Z_{12}}{Z_w}\left(1 + \frac{Z_{23}}{Z_{13}}\right) \quad . \quad . \quad (54)$$

$$\alpha_0 = \frac{e_{r03}}{e_{f12}} = \frac{\alpha_3}{1 + \dfrac{Z_{23}}{Z_3} + \dfrac{Z_{23}}{Z_0}} \quad . \quad . \quad . \quad (55)$$

(8.2.3) **Transition of waves across the points of connection.**

Equations (41)–(44) and (51)–(55) are valid only for the original waves. As soon as a wave reaches the neutral or any connecting point, other secondary waves are produced. As the lengths of the conductors and the wave velocities are equal, all incoming waves arrive simultaneously at the opposite ends of the conductors at a time given by

$$\Delta t = \frac{L}{3v} \quad . \quad . \quad . \quad . \quad . \quad . \quad (56)$$

after the head of the incident wave has reached the terminal 1. In equation (56) $L/3$ is the length of one section of the winding or one-third of the length of the whole winding per phase (see also Fig. 9).

The wave e_{f23}, which is the outgoing wave starting from the point 2 at the time $t = 0$, arrives at 3, if damping is neglected, with its amplitude unchanged; here it is the incoming wave e_{f32}. Similarly, the incoming wave e_{23} has the same amplitude as the outgoing wave e_{r32} and so on for the remainder.

There would be no difficulty in taking account of damping by applying a factor less than unity to each outgoing wave to convert it to the corresponding incoming wave.

The amplitudes of the outgoing waves may now be found from those of the incoming waves. As all waves travelling in any one conductor must obey the same differential equations, a second group of equations for the incoming waves may be set up, corresponding to equations (45)–(50) from the outgoing waves:—

$$\left.\begin{aligned} Z_1 i_{r12} + Z_2 i_{r23} + Z_3 i_{r30} &= -e_{r12} \\ Z_2(i_{r12} + i_{r23}) + Z_3 i_{r30} &= -e_{r23} \\ Z_3(i_{r12} + i_{r23} + i_{r30}) &= -e_{r30} \end{aligned}\right\} \quad . \quad (57)$$

and:—

$$\left.\begin{aligned} Z_1 i_{f21} + Z_2 i_{f32} + Z_3 i_{f03} &= e_{f21} \\ Z_2(i_{f21} + i_{f32}) + Z_3 i_{f03} &= e_{f32} \\ Z_3(i_{f21} + i_{f32} + i_{f03}) &= e_{f03} \end{aligned}\right\} \quad . \quad (58)$$

The equations may be simplified by introducing the currents which result from the superposition of the incoming and outgoing currents in each of the conductors at each point of connection. This may be written generally

$$i = i_f + i_r$$

At any point the sum of the incoming and outgoing currents is zero.

Thus for the point 2 in Fig. 9

$$i_{f21} + i_{r21} + i_{f23} + i_{r23} = 0$$

i.e.
$$i_{21} + i_{23} = 0$$

or
$$i_{21} = -i_{23} = i_2 \quad . \quad . \quad . \quad . \quad (59)$$

Similarly for the point 3:—

$$i_{32} = -i_{30} = i_3 \quad . \quad . \quad . \quad . \quad (60)$$

Similarly the general expressions may be abbreviated by putting

$$\left.\begin{aligned} i_{f12} + i_{r12} &= i_1 \\ i_{f03} + i_{r03} &= i_0 \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad (61)$$

$$\left.\begin{aligned} e_{f12} - e_{r12} &= e'_1 \\ e_{f23} - e_{r23} &= e'_2 \\ e_{r30} - e_{r30} &= e'_3 \end{aligned}\right\}, \quad \left.\begin{aligned} e_{f21} - e_{r21} &= -e''_2 \\ e_{f32} - e_{r32} &= -e''_3 \\ e_{f03} - e_{r03} &= -e''_0 \end{aligned}\right\} \quad . \quad (62)$$

The four voltage waves meeting at a given point of connection obey the equations

$$\left.\begin{aligned} &(\text{Point } 1)\ E_{f1} + E_{r1} = e_{f12} + e_{r12} \\ &(\ \ ,,\quad 2)\ e_{f21} + e_{r21} = e_{f23} + e_{r23} \\ &(\ \ ,,\quad 3)\ e_{f32} + e_{r32} = e_{f30} + e_{r30} \\ &(\ \ ,,\quad 0)\ e_{f03} + e_{r03} = E_{f0} + E_{r0} \end{aligned}\right\} \quad . \quad (63)$$

The following coefficients may now be defined:—

$$\left.\begin{aligned} e_{f12} - e_{r12} &= X_1 \\ e_{f23} - e_{f21} = e_{r21} - e_{r23} &= X_2 \\ e_{f30} - e_{f32} = e_{r32} - e_{r30} &= X_3 \\ e_{r03} - e_{f03} &= X_0 \end{aligned}\right\} \quad . \quad (64)$$

From Fig. 9 it follows that X_1 and X_0 express the modifications which waves arriving at the end of the winding undergo through apparent reflection, whereas X_2 and X_3 express the modifications suffered by waves continuing across a point of connection through apparent refraction. These four coefficients must be expressed as functions of the incoming waves. Introducing the differences between the two known waves meeting at each point:—

$$\left.\begin{aligned} D_1 &= E_{f1} - e_{r12} \\ D_2 &= e_{f21} - e_{r23} \\ D_3 &= e_{f32} - e_{r30} \\ D_0 &= e_{f03} - E_{r0} \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad (65)$$

With equations (62) and the known relation

$$e_{f12} + e_{r12} = 2E_{f1} - i_1 Z_l \quad . \quad . \quad . \quad (66)$$

it follows that

$$e'_1 = e_{f12} - e_{r12} = X_1 = 2D_1 - i_1 Z_l \quad . \quad . \quad (67)$$

$$X_2 = e'_2 - D_2 = e''_2 + D_2 \quad . \quad . \quad . \quad . \quad . \quad (68)$$

$$X_3 = e'_3 - D_3 = e''_3 + D_3 \quad . \quad . \quad . \quad . \quad . \quad (69)$$

$$e''_0 = e_{r03} - e_{f03} = X_0 = -2D_0 + i_0 Z_0 \quad . \quad (70)$$

From these equations, by adding the corresponding equations (57) and (58) to equations (45)–(50), and introducing the abbreviations (59)–(62), are obtained the equations

$$2D_1 = i_1(Z_1 + Z_l) + i_2 Z_2 + i_3 Z_3 \quad . \quad . \quad (71)$$

$$D_2 + X_2 = (i_1 + i_2)Z_2 + i_3 Z_3 \quad . \quad . \quad . \quad . \quad (72)$$

$$D_3 + X_3 = (i_1 + i_2 + i_3)Z_3 \quad . \quad . \quad . \quad . \quad . \quad (73)$$

$$D_2 - X_2 = i_2 Z_1 + i_3 Z_2 + i_0 Z_3 \quad . \quad . \quad . \quad . \quad (74)$$

$$D_3 - X_3 = (i_2 + i_3)Z_2 + i_0 Z_3 \quad . \quad . \quad . \quad . \quad (75)$$

$$2D_0 = (i_2 + i_3 + i_0)Z_3 + i_0 Z_0 \quad . \quad . \quad . \quad (76)$$

These six equations, together with (67) and (70), enable the four X coefficients to be calculated from the four known D coefficients.

An elementary transformation leads to the final equations:—

$$i_1 = 2 \times \frac{D_1 - D_2\dfrac{Z_{23}}{Z_{13}} + D_3\left(\dfrac{Z_{23}}{Z_{13}} - \dfrac{Z_3}{Z_2 + \dfrac{Z_0 Z_3}{Z_0 + Z_3}}\right) + D_0\dfrac{Z_3^2}{(Z_0 + Z_3)\left(Z_2 + \dfrac{Z_0 Z_3}{Z_0 + Z_3}\right)}}{Z_w + Z_l} \quad . \quad . \quad . \quad (77)$$

[Z_w being given by equation (51)]

$$X_1 = 2D_1 - i_1 Z_l \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (78)$$

$$X_2 = 2D_1 - D_2 - i_1(Z_{12} + Z_l) = X_1 - D_2 - i_1 Z_{12} \quad (79)$$

$$X_3 = X_2 + (D_2 - D_3)\frac{Z_{12} - Z_{23}}{Z_{13}} - i_1\frac{Z_{12}Z_{23}}{Z_{13}} \quad . \quad . \quad (80)$$

$$X_0 = \frac{-2D_0}{1+\dfrac{Z_0Z_2}{Z_{23}Z_3}} - \frac{\dfrac{Z_3}{Z_2}\times(X_3 - D_3)}{1+\dfrac{Z_{23}Z_3}{Z_0Z_2}} \quad . \quad . \quad . \quad . \quad . \quad (81)$$

The capacitances used in the numerical calculations are taken from published information,[4] and are as follows:—

$$\left.\begin{aligned} c_{12} &= 0\cdot00018\ \mu\text{F} \\ c_{23} &= 0\cdot0003\ \mu\text{F} \\ c_{30} &= 0\cdot00034\ \mu\text{F} \end{aligned}\right\}\text{per foot of concentric conductor}$$

It will be seen from the above equations that neither λ, l nor v influence the numerical calculations, so long as the ratio Z_l/Z_w is not altered.

WRITTEN CONTRIBUTION TO THE DISCUSSION ON THE ABOVE PAPER

Mr. W. D. Horsley: The paper is mainly a theoretical investigation of the distribution of surge-voltage stress in a concentric-conductor stator winding. The treatment appears to be thorough, but, as the author states, he has little experimental data available with which to check his conclusions. He has made a number of assumptions and approximations which are widely different from the actual conditions obtaining in practice, and many of the results obtained, and the conclusions reached, are incorrect.

During the past two years an extensive theoretical and practical research has been made on the surge voltage distribution in the complete windings of two concentric-conductor alternators, and many hundred oscillograms have been taken over a wide range of surge voltages. These investigations were made with impulse generators having outputs up to 12 kW-sec. (discharge capacitance $4\frac{1}{2}\ \mu$F) which were ample to give reliable and comparable test results and clearly demonstrate that the amount and distribution of insulation in the concentric-conductor winding is more than adequate to withstand surge-voltage conditions in practice.

One of the major simplifications adopted in the paper is the disregard of the effects of damping due both to eddy currents in the iron and copper and to the dielectric loss in the insulation. Experiments have demonstrated that the travelling-wave phenomena are rapidly damped out with a reduction to one-third of their amplitude in only 3 cycles of the main oscillations ($18\Delta t$). Consequently the amplitude of the star-point voltages are appreciably less than the values shown in Figs. 14 and 15, while the continued reflections up to $35\Delta t$, which are required for the development of the maximum values, are no longer relevant to the problem. A further error is introduced by the assumption that the inter-section capacitances are proportional to capacitance per foot run of the conductor. The effective lengths of the sections are not equal, and typical values of capacitance of a 37·5-MVA 33-kV alternator are as follows:—

$$C_{12} = 0\cdot08\ \mu\text{F};\ C_{23} = 0\cdot125\ \mu\text{F};\ C_{30} = 0\cdot065\ \mu\text{F}.$$

The assumption of two series of waves in a concentric-conductor alternator to allow for the effect of the iron is not substantiated in practice. Only one set of oscillations of the travelling-wave type occurs, the velocity being about 80 metres/microsec., and contrary to the theory expressed in the paper the surge impedance, which is low (about 125 ohms), is practically unchanged whether the neutral point is earthed or isolated. Following the initial penetration of the surge voltage the magnetic flux, initially restricted to the slot, gradually penetrates into the core until it links with the whole of the phase winding. Corresponding to this latter condition oscillations of extremely long period may be set up; they are not travelling waves and, as they are uniformly distributed through the whole phase, they do not appreciably stress the interturn insulation.

The actual distribution of capacitance reduces the figure of $83\%\,E$ given in Section (4·3) to 77%, while the additional effect of damping reduces the maximum inter-section stress in practice to only $60\%\,E$. When $Z_l = 500$ this stress is further reduced to about $25\%\,E$, a figure which is only one-third of the equivalent value of $75\%\,E$ derived for the standard type of winding. The long-period oscillations cause high stresses to earth only if surges of long duration are applied directly to all three phases with the neutral isolated. Tests show that wave tails of 100 and 3 000 microsec. under these conditions give rise to neutral voltages of $1\cdot0\,E$ and $1\cdot75\,E$ respectively, which are appreciably less than the usually accepted figure of about $2E$. Since, in practice, wave tails exceeding the former value occur very infrequently, the stresses at this point are unlikely even to approach those forecast in the paper.

The author seems to anticipate that actual results will not agree with his theory and states in his concluding paragraph that experimental work, presumably at reduced voltages, would be "subject to considerable errors due to the depth of penetration of flux into the iron of the core varying with the current in the conductors." In point of fact measurements made with impulse voltages ranging from 1 to 50 kV show no differences such as the author expects. Presumably the experiments mentioned in the footnote on page 502 were made on a cable in air, and while these results may confirm the author's theory they have little value when applied to an actual concentric-conductor alternator.

Typical curves of voltage distribution in a concentric-conductor winding obtained during the impulse tests mentioned with a 1/60-microsec. wave applied to one phase

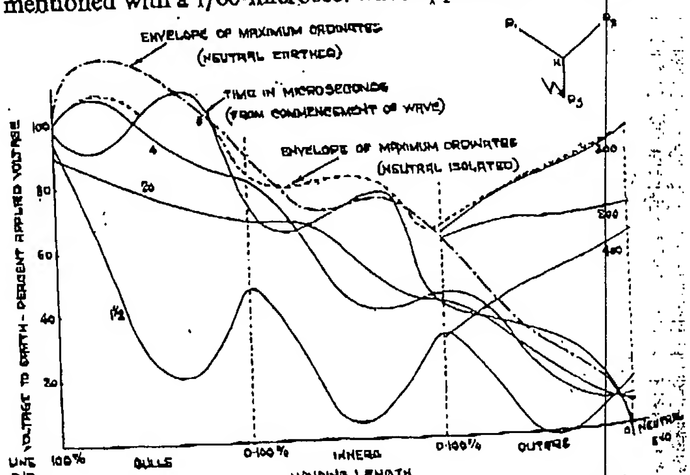


Fig. A.—Actual impulse voltage distribution in concentric-conductor h.v. alternator with 1/60 microsec. wave applied directly to one phase, neutral isolated.

with the neutral point isolated are shown in Fig. A. The envelope of the maximum ordinates for the neutral earthed condition is also shown in this Figure. The most unfavourable voltage distribution between sections for these two conditions and also for a surge applied simultaneously to three terminals with the neutral isolated is shown in Fig. B. These curves do not show concentration of stress

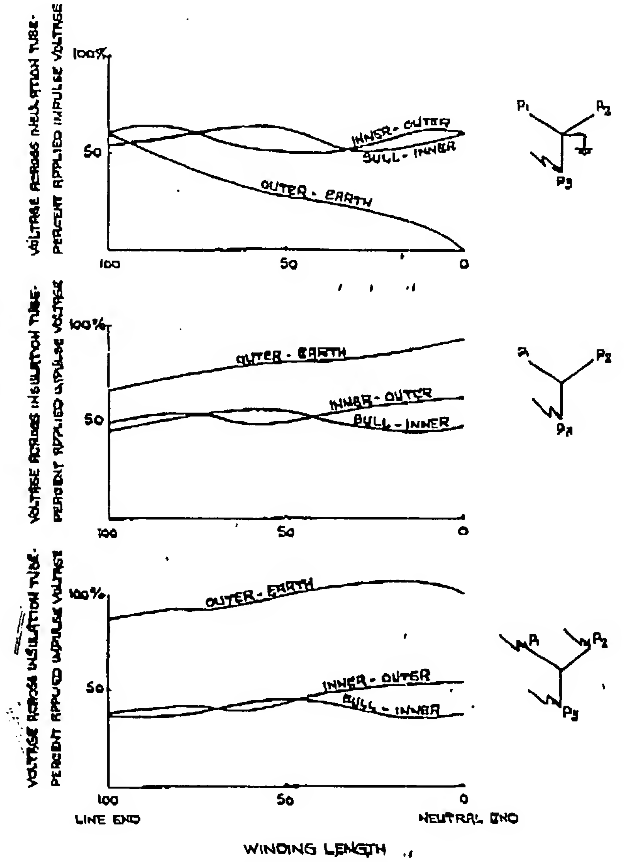


Fig. B.—Maximum voltage across insulation in concentric-conductor h.v. alternator for 1/60 microsec. wave applied directly to terminals, under various conditions.

at any point in the windings, and the maximum stress is maintained only for one or two microseconds before falling to the 50-cycle voltage distribution. Records were made up to 1 000 microsec. when all voltage differences had fallen to a low value. Tests with chopped and long wave tails do not show any increase in the intersection stress.

The difference between these results and those indicated by the curves previously published,* which were taken on a model winding of shortened length with a 1/5-microsec. wave and with an impulse generator of relatively small capacity, is not as great as the author expects.

Prior to the development of the turbo-type high-voltage alternator, a vast amount of experience had been gained with alternators operating at voltages up to 13 kV and occasionally higher under a wide range of service conditions. Alternators designed for 12 kV have operated successfully for many years on systems to which were directly connected long lengths of overhead lines insulated for 33 kV. In my experience breakdowns of alternator windings between turns or to earth owing to surge voltages have been rare, and where the former have occurred the reason has generally been inadequate insulation at this point.

The first high-voltage concentric-conductor alternator was installed in 1928, and since that date machines having an aggregate capacity of nearly 1 000 MVA have been commissioned. No difficulties due to impulse voltages have been experienced on any of this plant and the breakdown referred to on page 501, which was very carefully investigated, was found to be due to constructional causes. It has been shown that repeated impact of surges even of comparatively long duration causes little fatigue effect and does not cause deterioration such as might result from a high overvoltage which is sustained for some seconds or longer. Hence it seems evident that a failure due to surges would take place at the time of application of the surge, whereas the only breakdown cited by the author in support of his theory took place with the alternator running disconnected from the system.

The investigations which have been carried out on actual concentric-conductor windings show that the author is incorrect in his conclusion that the stress between the conductors of concentric-conductor windings is as high as that in the conventional winding. The author also states that it is unsafe to grade the insulation of any type of winding if it is operated with the neutral earthed without some form of surge protection. The disadvantage of providing full insulation to earth on all parts of the winding is the large amount of room required by the conductors, which in a normal winding results in an uneconomical design, particularly as the output of an alternator is reduced.

The concentric-conductor design has the advantage that while the high-potential and intermediate-potential conductors are fully graded it has been possible to increase the insulation thickness of the low-potential conductors to earth without appreciable sacrifice in economy of design. The insulation of the section connected to the neutral point, therefore, is adequate to withstand surge voltage stresses as well as the elevation of the potential of the neutral point caused by system fault conditions. The majority of the large number of concentric-conductor alternators in commission are operating with the neutral point isolated and without voltage-limiting devices.

If the author's conclusions were correct there would be no alternative to the fully insulated conventional design for high-voltage generation. In actual practice, with few exceptions the large number of high-voltage alternators in commission have concentric-conductor or graded-layer windings. The ability to withstand surges is only one of the many problems of high-voltage generation, and it may not be inopportune to point out that high-voltage generation with turbo-type alternators was only made possible by the initial adoption of the concentric-conductor design.

It is impracticable to deal here with all the points raised or to give many details of the tests which have been carried out, and it is hoped that it may be possible later to give full information in a paper on this subject.

Dr. E. Friedländer (*in reply*): Mr. Horsley's interesting contribution may, at first sight, appear to show that, while the correctness of the theoretical study is borne out by experiment for the threefold concentric cable in air, application to an actual alternator would lead to incorrect conclusions. However, in spite of some discrepancy—due

* *Journal I.E.E.*, 1940, 86, p. 366.

to the influence of the laminated iron—Mr. Horsley's figures and diagrams only serve to show how helpful the simplified theory is for an approximate estimate of the maximum voltages to be expected in an actual alternator. The main numerical results prove how closely the theory approaches reality, as seen from the following examples.

The maximum inter-turn voltage predicted under limit assumptions for the influence of the iron is 68 %, whilst Mr. Horsley's Fig. B gives 63 % in contrast to the 33 % which would follow from earlier publications. According to the paper the voltage of the outer conductor to earth with the neutral insulated should reach 100 % of the amplitude of a rectangular incident wave after about 70 microsec. In Mr. Horsley's experiments with a wave of 100 microsec. tail length the neutral reached 100 % of the voltage of the incident wave, and according to Fig. B a value of 106 % was obtained on the outer conductor with a 1/60-microsec. wave.

The voltage distribution shown in Fig. A at $1\frac{1}{2}$ microsec. after impact compares closely in character with that predicted from Fig. 7 or Fig. 9 for the original wave distribution. Detailed comparison is not possible as, unfortunately, the arrangement used for the tests has not been dealt with theoretically in the paper.

The neglect of damping cannot influence the main figures derived from the theory by more than a few per cent. If, in spite of damping, one-third of the amplitude has been found after a time $18 \times \Delta t$, this will show that the reduction of the amplitude at a time between $\Delta t/2$ and $3\Delta t/2$, when the first waves meet, will be well within the limits of accuracy that can be expected. It was not claimed that the extended diagrams were accurate. It was clearly stated that they were given for the sake of physical clarity rather than to show details.

Neglect of the differences in the effective length of the conductor sections is shown by Mr. Horsley himself to be quantitatively unimportant.

Mr. Horsley's statements regarding the influence of the iron are of great interest. This is a major problem which has still to be solved and which is too involved to be settled in a short discussion. It obviously affects all alternator windings, whether of the concentric or the conventional design. When the investigation was made more than 3 years ago, the comparison between the two types of windings was based on the assumption adopted by all earlier investigators that the slot surface could be treated as an earthed conductor. This assumption, however, cannot be quite correct. Attempts to estimate the actual effect of the iron in the case of the concentric-conductor winding have been mentioned in the paper. The maximum calculated stress to the bull insulation, which was 83 % without iron, was reduced to 70 % with iron (68 % with the revised capacity figures). However, the iron must exert an equivalent influence on the windings of standard design also. Recent investigations suggest that the relief of inter-turn stresses due to this influence is much greater than has been expected from hitherto accepted theories, and that in the conventional winding the inter-turn insulation is apparently protected by the iron even in the limiting case of zero surge impedance of the feeding line, because the high inductance provided by the iron is found to be mainly in the common earth path. It is hoped that these new investigations will be the subject of a later paper.

It appears that, even from an experimental point of view, the necessity of increased theoretical insight into the fundamental features of the various windings cannot be denied. This seems to be supported also by Mr. Horsley's reference to earlier experiments made on an "abbreviated model" which was intended to represent the surge conditions of a concentric-conductor alternator.* Rosen's arrangement consisted of a small portion of a threefold concentric-conductor winding the conductors of which were connected to tappings on an iron-cored choke, i.e. an auto-transformer, so that the normal frequency/voltage distribution would be equivalent to that due to the operating voltage in the alternator. It is obvious that if this arrangement is subjected to surge tests the concentric conductor acts merely as a group of cross-capacitances for the transformer winding. This could but lead to the favourable voltage distributions found with this model, and may have been responsible for the claims which have been made for the surge characteristics of these windings. The difference between these earlier results and the diagram (Fig. A) obtained now on a real machine, far from being negligible, is a convincing demonstration of the correctness of the theory.

The fact, mentioned by Mr. Horsley, that the only breakdown that occurred exactly at the middle of a section took place while the machine was disconnected, is, of course, no evidence that the theory is incorrect. While reference to the paper shows that the probability of breakdown due to travelling waves is greatest near the middle and near the ends of each section (see also Mr. Horsley's Fig. B for support of this conclusion), it does not follow that a surge breakdown cannot occur anywhere else.

Mr. Horsley's statement that the theoretical results obtained would not leave any alternative to the fully insulated conventional design for h.v. generation, cannot be accepted. It merely follows from the paper that h.v. alternators with fully graded insulation should have their star point either earthed or, if possible, properly protected. If, on the other hand, the insulation of concentric-conductor alternators is appropriately adapted to the surge stresses which may occur, the total amount of insulation required must be considerably greater than that necessitated by the operating voltage. Addition of the maximum relative-stress figures which have been found experimentally for the different sections of the winding by Mr. Horsley, yields a total, not of 100 %, but of 231 % for the 1/60 wave. In addition, the increased insulation which is required mainly for the outer conductor affects that section which has the greatest surface area, and it therefore seems surprising that this insulation can be sufficiently increased without rendering the design uneconomical. Whilst one does not wish to minimize in any way the pioneer work which has been accomplished in the development of the concentric-conductor alternator, Mr. Horsley will probably agree that the advantages obtainable with this design have at least been over-estimated in the earlier publications. I hope that it may be possible to make further use of the theoretical method applied in the paper when Mr. Horsley's detailed test results are available, together with more advanced investigations concerning the influence of the laminated iron of the stator core.

* For a description of such an abbreviated model, see J. ROSEN: *Journal of the Junior Institution of Engineers*, 1934, 45, p. 1.

DISCUSSION ON "OPERATING EXPERIENCE WITH HIGH-VOLTAGE ALTERNATORS"*

FURTHER WRITTEN CONTRIBUTION TO THE GENERAL DISCUSSION†

Mr. A. E. F. Spence (South Africa) (*communicated*): Consideration of the points dealt with in the paper seems to indicate that the h.v. neutral point of the voltage transformer should be insulated from earth. Can the author say why this was done in the first Brimsdown machine, and not in the second one? Mention is made of the cost of a high-voltage bushing on the transformer chambers of switchgear of the phase-isolated type. This seems to be a defect of this type of gear. I should be glad if the author could give any comparison of the cost of such bushings and that of apparatus for suppressing neutral inversion.

I do not follow the author's explanation of the failure of machines No. (4) and No. (6) at Salt River. This might well apply to periods when the machine was running up or down disconnected from the system, and under full or partial excitation. The failures occurred after some hours on load, particularly that of No. (4) machine, which had been running all day at nearly full load.

Finally, does the author think any improvement would accrue from running 33-kV alternators in hydrogen?

[The author's reply to this discussion will be found on page 684.]

NORTH MIDLAND CENTRE, AT LEEDS, 17TH FEBRUARY, 1940

Mr. F. Gurney: To go back 11 years in the history of 33-kV generation is to go back to the pioneering days. The justification for this pioneering is evident from the Table, giving a list of high-voltage alternators that have been built. This list indicates that there is a demand for 33-kV generation. Many city undertakings are already solving their problems of switchgear limitations and cable congestion by adopting 33-kV distribution.

The author analyses under three headings the troubles encountered: (1) conductor insulation, (2) joint insulation, (3) over-voltage caused by neutral inversion.

I agree that there should be no trouble whatever with conductor insulation. Only one accident of this sort is recorded, and plenty of evidence is given to suggest that the care now taken should prevent future troubles. But the whole conception of the concentric-conductor design is based, apparently, on the fear of conductor trouble. The concentric conductor is merely a voltage-grading device. Equally effective voltage-grading can be achieved with the condenser-bushing type of conductor, which does not lead to any troubles such as are described under the heading "Joint Insulation." We can draw a parallel with the old-type concentric cable, which, although having excellent qualities, cannot be used up to high voltages on account of trouble at the joints.

I disagree with the author's remark (page 350) "The advantage of thoroughly impregnating completed windings with insulating varnish in order to eliminate air spaces is recognized widely, and the only reasons for not applying this treatment to large machines are the high cost of, and large amount of space occupied by, the necessary equipment." Impregnation under vacuum should be done during the process of making the individual windings, when it is possible to get the varnish to the points where it is needed.

I notice on page 351 the remark "After the cycle has been completed, dry heated air is circulated through the tank in order to oxidize the varnish." I presume oxidation of the varnish is the process of hardening it. Emphasis is laid on getting the varnish into every nook and corner; but how then does the oxygen get there also for hardening purposes?

On page 345 it is stated "The bar was replaced in a few days, and this experience served to demonstrate the rapidity with which a bar can be replaced in the concentric type of winding." Was it not necessary for the machine to go through the impregnating plant?

Mr. W. T. J. Atkins: The author has been unfortunate in that some of the machines he has designed have been subjected to excessive voltage-stresses due to conditions of operation which he had no reason to foresee. The circumstances emphasize the importance of considering methods of earthing in relation to systems or assemblages of plant as a whole, rather than in relation to individual items of equipment.

The paper refers generally to the phenomena classed as neutral inversion, and points out that they are usually encountered in connection with instrument transformers associated with phase-isolated switchgear. I had personal experience of such a phenomenon a few years ago, when an oscillograph showed the presence of parasitic voltages having a frequency slightly differing from half the system frequency. The effect was one of the types described in the author's Bibliography, and according to the published information it should have been possible to prevent it by connecting damping resistors across the voltage-transformer secondary terminals, but attempts to do this proved unsuccessful. Fortunately, the abnormal voltages produced were not in this instance of a dangerous character, so that the occasional production of neutral inversion, although inconvenient, was harmless.

Prof. E. L. E. Wheatcroft: It is a well-known fact in laboratory practice that every item of equipment, and

* Paper by Mr. W. D. Horsley (see 86, p. 345). † See 86, p. 354.

particularly equipment liable to high voltage, should have its potential fixed with respect to earth; and there is no doubt that this principle still holds when the plant is removed from the laboratory to a power system. In the past, power engineers have often been in the habit of regarding the neutral-earthing equipment as being designed merely with the object of relay operation, whereas there is little doubt that its primary purpose ought to be the fixing of system potentials. Looked at from this point of view, the fear of multiple earthing which has been engendered in power-station engineers by earlier Post Office requirements may easily have unfortunate results. My point is that it is far better from the point of view of fixing potentials to have too many earthed points rather than too few. In particular, it should be realized that a generator which is being run up and is about to be synchronized is a separate system, as also is a generator which is being disconnected. It is therefore essential that the potentials of these generators should be fixed by a neutral-earthing device, and that there should be temporarily (for perhaps only a matter of seconds) a multiple earth on the system just when these generators are being connected.

It is clearly much easier to apply the principle to a generator which is being connected than to one which is being automatically disconnected on fault, and it is probably just on the latter occasion that the system is most liable to abnormal voltages. Nevertheless, it is, as Mr. Atkins said, most desirable that the neutral-earthing arrangements should be worked out as a complete system, and this should include if necessary automatic arrangements which ensure that a generator when being disconnected is not left isolated from earth. Otherwise voltages are determined by strange things, such as capacitance, of which the designer has no knowledge and over which the operating engineer has no control.

Mr. R. Wall: Electrical engineers have for some time been looking forward to 66-kV generation, and I think the author is helping to make it an accomplished fact.

Mr. Gurney mentioned that 33-kV distribution is popular; but 66 kV would be a more convenient voltage to use for supplying the C.E.B., which takes the bulk of the load from the big power stations. So far as transformer efficiency is concerned, the difference is small between 11-kV to 66-kV and 33-kV to 66-kV transformation. I feel that whilst we are doing a tremendous amount of development with 33-kV generation, we should regard this only as pioneer work for 66-kV generation.

[The author's reply to this discussion will be found on page 684.]

NORTH-WESTERN CENTRE, AT MANCHESTER, 19TH MARCH, 1940

Mr. J. A. Kuyser: I think we must concede that in general the concentric-conductor alternator has proved successful, but I believe there are other and better ways of dealing with the problem of 33-kV generation.

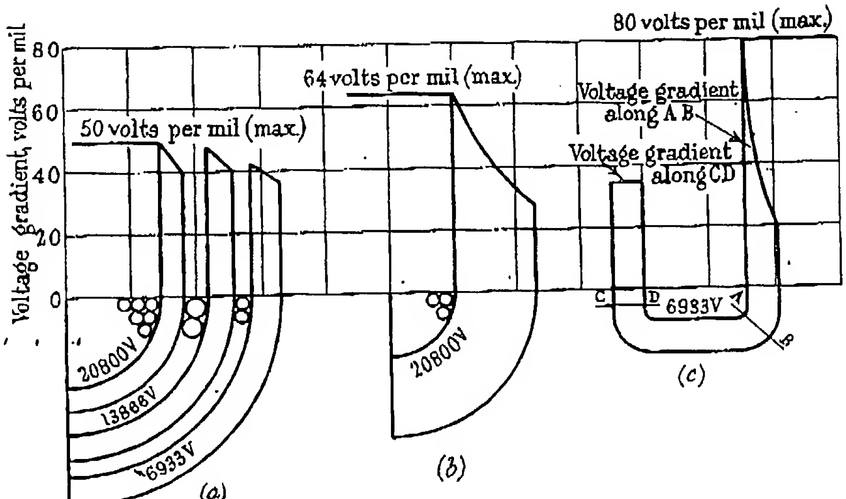


Fig. C.—Curves showing voltage gradient through insulation on various types of conductors. (Increase in gradient due to strands of cable = 23 %.)

(a) Concentric conductor for 30 000-volt alternator. (b) Single-core conductor for 36 000-volt alternator. (11 000 volts) alternator design. (c) Rectangular slot for low-voltage

I notice that a large percentage of the troubles mentioned in the paper have occurred at the joints. In particular, the failure at Swansea was due to a combination of overheating at the joints and defective insulation. Regarding the first Brimsdown alternator, which has been in operation for 11 years, the power factor of the load at Brimsdown is unity, and since the generator was designed for 0·8 p.f. it must have been operating at 80 % of its rated current, and therefore at two-thirds of its normal temperature-rise on the end connections. This has been perhaps very fortunate in that it may have prevented trouble similar to that at Swansea, which might have prejudiced operating engineers from the start against 33-kV generation.

Regarding the joint construction shown in Fig. 3, I quite agree that the insulating bushes are a very important feature of these joints. Their function is somewhat similar to that of the stress cones used in cable

boxes. There is a bush between the bull and the inner conductor, and one between the inner and the outer, but there is no bush between the outer and the core. This is a bad feature, because the creepage distance between the core and the outer is relied upon as being an equivalent to a bush, and this distance is too short for the purpose. The potential of the outers is normally only 11 kV, but the potential due to feeder faults and surges is considerably greater.

There is considerable danger of failure due to surges, particularly if the generator is operating on an overhead line, even if there is a short length of cable connected between the overhead line and the generator. In the case of a feeder fault, the inner section reaches a voltage of 24 kV to earth, but there is a likelihood of a surge emanating from the fault, particularly if the star point is insulated. We have made an investigation with the new type of recurrent-wave cathode-ray oscillograph, and we have found that the wave travels through the winding and is reflected at the insulated star-point, and at the moment of reflection the voltage is almost twice the voltage of the incoming wave.

If an earthing resistor is used, the reflection can be eliminated, and it is advisable to have a resistor between the star point and earth on every generator which is connected to the busbars (multiple earthing). The resistor should have a value rather less than the surge impedance of the winding, which is of the order of 500 ohms. A resistor of about 200–300 ohms is generally used.

The claim is made for the concentric-conductor alternator that it is immune from surges due to the high capacitance between sections. The published curves (86, p. 366) show that the potential difference between winding sections is approximately one-third of the voltage of the incoming wave when the star point is earthed. It would be interesting to see curves taken with the star point insulated, which will show higher internal voltages. The maximum voltage between turns of the single-conductor winding is approximately one-third that of the incoming wave if the star point is insulated; and the two types of winding are therefore similar in their behaviour as regards surge distribution. The single-conductor winding has the advantage of full insulation on each conductor, and double full insulation between turns.

Fig. C gives the manufacturer's curves showing the distribution of voltage gradient through the insulation on various types of slot conductors. The maximum gradient on the bull conductor is given as 50 volts per mil. On the 11-kV rectangular conductor, at (*c*), the stress at the four corners is given as 80 volts per mil, this high value being due to the stress concentration at the corner. The stranded cable shown at (*a*) has a small radius to every strand, however, and there is a stress concentration of 23 % at every one of these strands. A similar stress exists on an overhead transmission line, the corona limit of a stranded cable being lower than that of a smooth conductor. If we allow for the concentration due to stranding the gradient becomes 62 volts per mil.

In order to control the stress distribution in the single-conductor winding, each conductor is made in the form of a condenser bushing by means of conducting shields (Fig. D). Each grading shield has a potential which can be calculated in the same way as that in a condenser bushing. There is an extra stress due to the fact that the bar is rectangular, and also an extra stress due to the corners. These stress concentrations can be determined by means of the method described by Cockcroft.* The average gradient between the conductor and the inner shield is about 16 % higher than the average over the whole thickness, which makes it about 52 volts per mil. The extra stress at the corners is 25 %, so that there is a maximum local stress of 65 volts per mil. The gradients

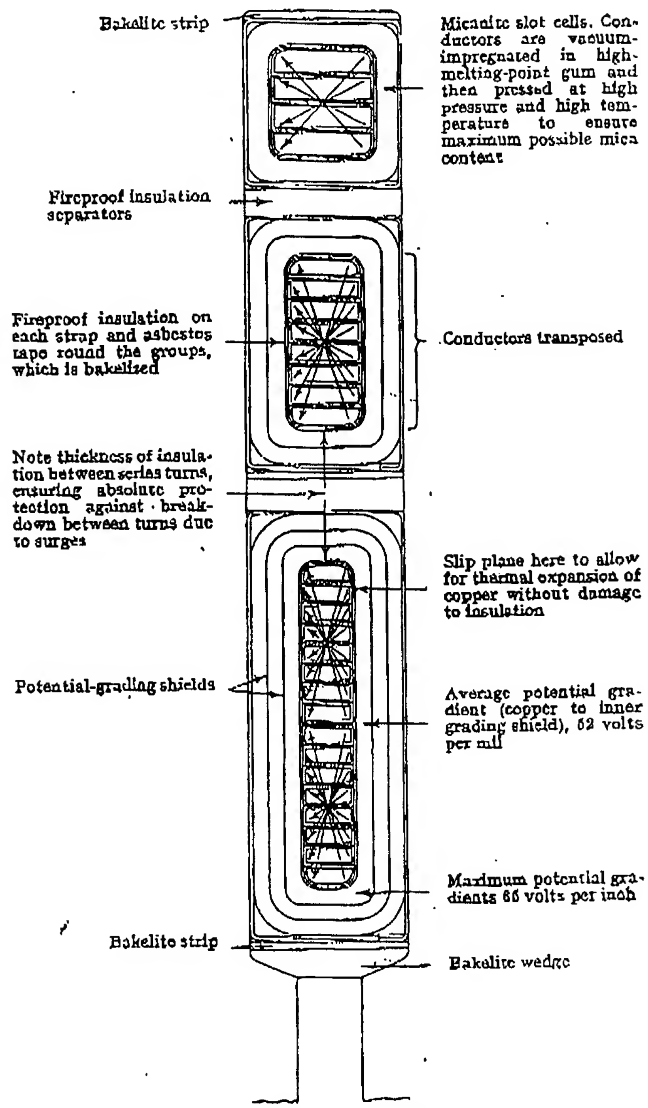


Fig. D.—Stator slot, 33 000 volts.

obtainable in the rectangular conductor with grading shields are therefore the same as those obtainable by means of a concentric conductor. The longitudinal gradient at the end of the conductor outside the core, obtained by means of the grading shields, is similar to that of a condenser bushing. The local gradient at the end of the core is divided into three smaller gradients which are roughly equal.

I take the opportunity of giving some further details of the single-conductor winding. It consists of three com-

* *Journal I.E.E.*, 1928, 66, p. 385.

pletely separated windings wound for 11, 22 and 33 kV respectively. The 11-kV winding is at the bottom of the slots, and this winding is first completely finished; the 22-kV and 33-kV windings are then placed in position.

It will be noted that the bars join the connectors in a large curve, and it is very easy for the workshop to insulate the joints perfectly. The insulating tape can be applied uniformly, almost as on a cable, and the thickness of insulation can be made adequate. As a result the joint is almost as strong as the remainder of the end-connectors. A complete conductor and a connector jointed together were immersed in salt water, and after 5 weeks a voltage test of 80 kV failed to cause a breakdown, but flashover took place between the connector and earth over a length of 4 ft.

Mr. F. A. Youngmark: Some of the failures which form the subject of the paper were caused by conditions external to the machines, such as neutral inversion or the presence of salt and moisture in the closed air circuit. Can the author state how the entrance of salt and damp air into the Salt River alternators was prevented? In practice, it is difficult to keep the alternator closed air circuit completely free from leaks, and in attempting to do so there is a risk of reducing the internal pressure on the high-pressure side of the ventilating fan down to, or even slightly below, atmospheric pressure, which of course involves a partial vacuum on the inlet side of the fan. If this condition exists there is a risk that oil vapour from the bearings may be drawn into the alternator. The usual method of preventing this is to arrange a small leakage path in connection with the external atmosphere on the inlet side of the fan, and to pass any make-up air through a filter. By this means the whole of the closed circuit is maintained at or above atmospheric pressure, assuming there is no excessive leakage on the delivery side of the fan. Was this practice adopted at Salt River, and, if so, was the filter effective in keeping the cooling air free from salt and moisture?

Other failures have been caused by weaknesses in the alternators. Two of the breakdowns on the second Brimsdown machine were due to actual punctures of the insulation tubes, but it seems clear from the paper that the cause of these failures is known and has been eliminated by better manufacturing methods, testing and inspection. The remaining breakdowns have involved the T-joints between the slot bars and the end connections. Anyone who has had the opportunity of examining one of these joints in detail cannot have failed to be impressed by the high standard of design and workmanship displayed in its manufacture, and that this type of joint can be made as reliable as any other part of the winding is proved by the fact that the first 33 000-volt concentric-conductor alternator has run for over 11 years without trouble.

The fact that one or two later machines have not been equally satisfactory can be explained by considering manufacturing conditions. The progress of the first machine of a new type through the shops is watched with anxious care by its designer and by everyone else concerned, and there is general relief when works tests and operation at site show that hopes and expectations have been realized. The process of winding a large alternator involves great care and skill on the part of the workmen. While inspection of machining processes can be both exact and complete, it is far more difficult to carry out continuous inspection during processes such as winding and the application of insulation. The need for close inspection is perhaps greatest after the novelty of the first machine of a new type has worn off, and until labour has, by frequent repetition, been fully trained in what may at first be novel work. More thorough inspection would no doubt have led to the rejection of the defective mica bushes referred to by the author.

Now that the importance of these small points is realized, the stator end-winding joints (Fig. 3) are no longer a source of weakness. The company with which I am connected has recently carried out an extended series of breakdown tests on these joints, and in every case failure has occurred by puncture of the insulating tubes surrounding the conductors, and not between joints.

Mr. W. Kidd: Our operating experience with a 71 500-kVA 33-kV machine has been entirely satisfactory; during the past 2 years the set has been on load for 96·5 % of the time, and the load factor has been 88 %. Experience elsewhere also has demonstrated that 33-kV machines are reliable if the conditions on the system are satisfactory. Some of these conditions the machine designer does not bother about. In new stations the matter is fairly straightforward, but in old stations generating at a lower voltage more difficulties present themselves.

During consideration of a scheme for the installation of four additional machines, I was reluctantly forced to the conclusion that the necessity of flexibility of arrangements for load transfer to various feeder sections during various stages of station loading, and also for dealing with short-circuit kVA, made the selection of a lower generating voltage the better proposition.

The machine characteristic in which the station designer is much interested is its reactance. What does the author consider is the maximum percentage reactance that can safely be adopted? I have used a figure of 25 %.

The cable connections to the machines should be very carefully designed; for civil-engineering reasons I prefer that the terminals should be arranged in the orthodox manner at the end of the machine. One maker, however, arranges the terminals on the side of the machine. Does the author see any objection to this? In one case at least I suspect that the ozone noticed comes from badly designed bare-copper connections to the set. Our practice has been to bring cables to the machine and make a good insulated connection to the windings.

Neutral inversion can be avoided, and should not be a cause of trouble in the future. The neutral of our system is earthed, and at the maker's request we also earth the neutral of the incoming machine; after the set has been connected to the busbars one of the neutral circuit-breakers is opened. I should certainly prefer not to leave the system unearthed.

I believe the earlier 33-kV machines had rather a low efficiency at low loads, when compared with that of a lower-voltage set. This is not a matter of great importance, because large sets are not operated at low loads, but I should like to know whether this characteristic has been changed on the author's later sets.

He mentions that, in a number of cases, trouble has been experienced due to heating of the neutral liquid resistor. If the electrodes were steel discs I would

suggest that they were, to a large extent, the cause of the trouble, owing to skin effect causing heating of the disc. A horizontal plate is a bad heat-dissipator, and heating becomes cumulative. The fitting of copper cylinders would improve matters.

Does the author see any disadvantage in the use of 33-kV machines in stations where they would be taken out of commission every night and run on light load for half an hour every midday?

Mr. H. G. Bell: About 2 years ago it was necessary for us to carry out some tests on protective gear which involved the application of short-circuits to the 132-kV grid system. The most convenient arrangement involved feeding an isolated section of the grid from a 50-MW generator wound for 33 kV. We approached the manufacturers regarding the use of the machine for this purpose, and they raised no difficulties whatever. The tests were duly carried out, and the generator showed no signs of distress. This indicates the faith the designers themselves have in the robustness of the 33-kV winding.

Mr. J. L. Carr: With high-voltage alternators some ozone generation is to be expected; and on 33-kV machines the effect is likely to be much more pronounced than on lower-voltage machines. The machine referred to by Mr. Kidd, however, has caused no perceptible odour during its period of operation, although a pronounced smell of ozone has been noticed near similar machines in another location. The method of connection may possibly have a marked influence on this matter: in the first case, cable connections are continued to the machine terminals, whereas in the other case, bare copper connections are employed; and increased discharge from these connections is to be expected.

The neutral-earthing of high-voltage generators is apparently a matter on which a good deal of divergence of opinion exists, but presumably the conditions, so far as the machines are concerned, must be improved by maintaining the neutral earthed through a resistor. Some minor difficulty due to boiling was experienced in one case where a liquid resistor was used, although this was the only system earthing point. The current flowing was primarily a triple harmonic, with a higher harmonic superimposed. The effect was not noticed when the normal metal-grid resistor was used, and only a slight increase in temperature was observed. The difference was, of course, due to the different temperature characteristics. The author states that operating engineers consider the possibility of losing the system neutral to be a normal operating risk. That was the case even with lower-voltage systems, but with 33-kV systems the risks are considerably greater. In at least two cases in other districts, of which I have some knowledge, the loss of the 33-kV neutral during a period in which faults persisted on other connected apparatus was responsible for more extensive consequential damage. Each case should therefore be considered on its merits. In one large undertaking where the busbar system is fully sectionalized, it is now considered desirable not only to earth the neutral of the direct-generating machine, but also to maintain an earthed neutral on another section, so that in the event of one machine being disconnected the system will still be earthed. Separate resistors are to be used, and direct coupling of the neutrals avoided. So long as the busbar sections are loosely coupled, it would appear, from preliminary observations, that the risk of excessive circulating current is not likely to be serious.

Mr. G. H. Sammons: The principal causes of trouble with concentric-conductor alternators are the dangers of neutral inversion and the difficulty of making satisfactory end-connections; the improvement of these is entirely in the hands of designers. Can the author give his reasons for stating that neutral inversion will not occur again? Can a machine be so designed that neutral inversion is impossible?

The author's method of improving end-connections appears to me to be a somewhat "patchy" treatment, and I am of the opinion that some major modifications will have to be made before a permanently satisfactory end-connection is produced.

Mr. W. D. Sutcliffe: The use of metalclad switchgear appears to have led the generator designers into a certain amount of trouble, because it caused them to use three single-phase voltage transformers connected in star across the alternator, and this is not very good practice. It would have been worth while to alter the gear so that single-phase transformers could be used.

With regard to the earthing of alternators, there is no harm in earthing the neutral point of each machine. This has been done in one station where there are two 33-kV alternators running in parallel, and so far it has not caused any trouble. The author recommends that the earthing resistor should be of such a value as to allow the full-load current to pass, but this seems to be rather a high upper limit where there are overhead lines on the system, and where the biggest trouble is earth faults. Full-load current passing through the earth fault might cause a considerable amount of damage to the overhead lines.

As regards the earthing of 33-kV systems, it is essential that the neutral earth-connection should be maintained on all parts of the system as far as is practicable. In the case which Mr. Carr mentioned, where serious damage was caused by part of the system becoming earth-free, there was no earthed neutral on the part of the system involved.

One point which the author does not mention is the question of preventing high voltages on the alternators caused by surges passing along the overhead lines, such as occur when lightning strikes the line. Is it necessary to fit spark-gaps to the machine? Several machines have been damaged from this cause.

Mr. W. N. Kilner: For comparison with the author's Table of high-voltage concentric-conductor alternators, Table A gives a list of single-conductor type high-voltage turbo-alternators built, or at present under construction, in Manchester. These machines, of a total capacity of 688 310 kVA, have stator windings of the single-conductor type in which each series turn is in a separate coil, and the insulation to earth is graded in three or four steps between the star point and terminal ends of the winding. No faults or troubles have been experienced with any of the machines in service.

The smell of ozone seems to worry a number of operating engineers, but it should not cause alarm as it has been proved that the minute discharges which produce ozone do not damage the micanite insulation of modern turbo-alternators. The 20 000-kW 11 000-volt turbo-alternators installed 25 years ago in the North

Tees power station were among the earliest machines in this country to create a noticeable smell of ozone, and they were also among the first of the machines to operate with closed air circuits. They were 40-cycle alternators, and a few years ago were re-wound for 50 c./s., but before the old windings were stripped they were pressure-tested to breakdown, which occurred at 40 000 volts. The stator conductor insulation was carefully examined for any signs of deterioration due to ozone or discharges, but although the slot liners were found to be riddled with small punctures the mica insulation immediately under the liners was undamaged. I have examined a large number of machines of various voltages up to 33 kV in various power stations, and the machine which I find gives the strongest smell of ozone is an 11 000-volt generator. It does not give any trouble, and to my knowledge no trouble associated with ozone has ever occurred on turbo-alternators.

When the original paper by Sir Charles Parsons and Mr. Rosen* was read, I, among other speakers, suggested that a 33-kV alternator could not have as high an efficiency as an 11-kV machine. Since then, the author has had a number of years of operating experience with 33-kV machines, with opportunity to test their efficiency, and it would be interesting to know whether they have proved to be more efficient than 11-kV machines, and if 66-kV machines are expected to be still more efficient.

With reference to neutral earthing, care must be taken when installing neutral-earthing resistors to ensure that they are adequate to carry the triple-harmonic currents. Liquid earthing resistors have a negative temperature-coefficient, and unless they are of ample capacity there is a danger of the liquid boiling away. If the resistor is connected in series with a small reactor a smaller resistor can be employed than would otherwise be required. The reactor will limit the triple-harmonic current without affecting the 50-cycle fault current or the normal operation of the protective gear.

Mr. S. R. Mellonie: The opening of the connection between the neutral point and earth does not necessarily cause trouble or damage. On the contrary, I know of two cases where it saved the situation on a 33-kV cable system by interrupting a busbar fault.

With reference to the proportion of the total reactance which is changed from transformer reactance to alternator reactance when one puts in a 33-kV set compared with the usual arrangement of machine and transformer, does the decrease in percentage of real reactance result in a more stable machine?

* *Journal I.E.E.*, 1929, 67, p. 1065.

Table A

LIST OF HIGH-VOLTAGE TURBO-ALTERNATORS OF THE SINGLE-CONDUCTOR TYPE, IN SERVICE OR ON ORDER

Name of purchaser	No. of machines	Destination	Voltage	Speed	Rating
			kV	r.p.m.	kVA
Belfast Corporation	1	Harbour	33	3 000	37 500
Bradford Corporation ..	1	Valley	33	3 000	37 500
Cardiff Corporation	2	Roath	33	3 000	37 500
County Borough of Ipswich	2	Cliff Quay	33	3 000	56 250
Liverpool Corporation ..	2	Clarence Dock	33	1 500	66 666
London Power Co.	1	Deptford	22	1 500	58 800
Manchester Corporation ..	1	Barton	33	1 500	71 428
North Metropolitan Power Station Co.	1	Brimsdown "A"	33	3 000	38 800
	1	Brimsdown "A"	33	3 000	25 000
	1	Brimsdown "B"	33	3 000	43 600
	1	Brimsdown "B"	33	3 000	19 550
	1	Willesden	33	3 000	35 300
				Total	668 310

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSIONS

Mr. W. D. Horsley (*in reply*): In reply to Mr. Spence, the switchgear connected to the first high-voltage alternator at Brimsdown is of the open type, and this fact enabled the voltage transformers to be connected between phases as shown in Fig. 2. Two single-phase units were provided, and connected in open delta in accordance with accepted practice for metering transformers.

The switchgear for the second high-voltage alternator at Brimsdown is of the phase-separated type, and five single-phase voltage transformers in separate casings with the neutral end of the winding earthed to the casing were provided. While it would have been permissible to make a small sacrifice of the principles and advantages of phase separation by isolating the neutral point of the voltage transformers, this condition would have necessitated fully insulated transformers of increased size with larger tanks in addition to the neutral-point bushings. It is not possible to give a reliable comparison of the costs, but such an arrangement would be more expensive than the relatively simple measures required to suppress neutral inversion, as well as being difficult to accommodate in the existing switch panels. An alternative method

would be to connect the voltage transformers directly across the alternator instead of at the switchgear.

It is explained in the paper that the evidence indicated that the failures at Salt River originated in the flashover of the lead extension insulation which occurred while the machines were on load, and that neutral inversion was a contributory factor.

The main advantages claimed for hydrogen cooling, i.e. improvement in efficiency and reduction in the operating temperature of the alternator, would be obtained equally with high- and low-voltage alternators. Hydrogen has also a theoretical advantage in that the formation of oxygen compounds owing to corona would be eliminated; no difficulties due to this cause are experienced in either low- or high-voltage air-cooled machines.

Mr. Gurney is correct in stating that the concentric conductor is a voltage-grading device; and I would add that it was only the introduction of this principle, by Sir Charles Parsons and Mr. J. Rosen, which made possible the development of the high-voltage turbo-type alternator 11 or 12 years ago.* Theoretically the condenser-bushing type of conductor produces the same result, but the concentric conductor has the advantage that the voltage gradients are controlled by the potential generated in the conductors. In the condenser bushing the potentials of the conducting sheaths are determined not only by the capacitance but also by the conductance of the insulation. It is doubtful whether there is any means of ensuring that the insulation resistance of built-up mica insulation is uniform, and changes in both resistance and capacitance would take place with variations in temperature gradient. It is probable that in service the potentials of the conducting sheaths vary widely from their correct values. The conducting layers also have the disadvantage of connecting in series the weaker places in the layers of insulation, thus increasing the risk of breakdown.

As is mentioned in the paper, the concentric conductors are impregnated under high pressure during construction. The impregnation of the completed windings and the joint insulation is an additional process which has obvious advantages. The impregnating medium used is hardened on the surface by oxidation, but it also has the property of setting throughout the body of the varnish. It has the advantage that it does not become brittle, and retains a large degree of flexibility. When the alternator mentioned on page 345 was constructed it was not the practice to impregnate the complete stator. The replacement of a bar in a modern design is unlikely, but if necessary it would not be difficult to arrange for re-impregnation of the complete windings.

Mr. Atkins and Prof. Wheatcroft refer to the importance of earthing, and I am in general agreement with their views. Mr. Atkins's experience with neutral inversion is interesting.

In reply to Mr. Wall, the construction of a 66-kV generator is feasible, and in this connection the experience gained with 33-kV concentric-conductor alternators is invaluable.

It is satisfactory to have Mr. Kuyser's agreement in regard to the success of the concentric-conductor alternator, but I am unable to agree that there is any better method of dealing with the problem of high-voltage generation. The only difficulty experienced with joints has been that met with at Swansea, where the load conditions have been less onerous than at Brimsdown. (Although not shown in Fig. 3, a bush is normally fitted on the outer conductor as an additional precaution.) The maximum voltage which can occur from the outer to earth is 23 kV. The insulation provided is suitable for an alternator of this voltage, and the creepage distance is ample to meet all conditions of operation. I agree with Mr. Kuyser's recommendations to earth the neutral point in order to prevent over-voltages, and particularly in order to prevent high surge voltages with the type of winding he describes. The value of the surge voltage at the neutral point is dealt with in my reply* to Dr. Kahn's contribution to the discussion.† Further surge tests have now been completed which confirm the advantages of the concentric-conductor winding, and it is hoped later to publish some of the results, including a comparison of the surge-voltage distribution with the neutral point of the alternator earthed and isolated. In the concentric-conductor winding the thickness of the insulation to earth of the outer conductor can be increased very simply and economically in order to meet over-voltages, but in a graded winding with separate conductors much of the advantage of grading is lost if the insulation thickness on the low-voltage (11 kV) winding is not kept to a minimum.

I agree that the effect of the stranded conductor is to give a theoretical increase in the potential gradient near the conductor surface of about 23 %, but the actual increase is much less. This point was investigated some time ago when dielectric-loss and breakdown tests were made which showed that there was no difference between a smooth and a stranded concentric conductor. I have referred to the condenser-bushing type of conductor in my reply to Mr. Gurney. The tests described by Mr. Kuyser on a conductor bar and joint immersed in salt water are of interest. Similar, if not more onerous, tests were made some time ago on concentric conductors and joints which were maintained for many weeks at 75 % above normal voltage in a salt-laden atmosphere of 100 % humidity at a temperature of 67° C. At the same time full-load current was passed through the bars and the temperatures were varied over a wide range in order to simulate load cycles. No signs of deterioration were observed, and the conductors and joints later withstood a pressure test of over 40 kV.

In reply to Mr. Youngmark, the method of sealing the air coolers in the foundation block at Salt River was not satisfactory and air leakage developed. In addition, difficulties experienced with the water supply to the air coolers necessitated running the alternators on the emergency open-air circuit for considerable periods. These troubles were readily overcome, and it was not found necessary to adopt any special measures such as the provision of a special inlet and filter for make-up air. Mr. Youngmark's explanation for a weakness being found in the joint of an alternator after the satisfactory experience with the first machines, is no doubt largely correct. A technique of making and insulating such

* "Direct Generation of Alternating Current at High Voltages," *Journal I.E.E.*, 1929, 67, p. 1065.

* *Journal I.E.E.*, 1940, 86, p. 364. † *Ibid.*, 1940, 86, p. 365.

joints has been developed which is simple and reduces the danger of faulty execution to a minimum. His confirmation of the soundness of the joints from tests which he has carried out is very satisfactory.

Mr. Kidd states that 33-kV machines are reliable if the conditions on the system are satisfactory. Experience with the concentric-conductor machine shows that it is as reliable as a low-voltage design whatever the system conditions. The reactance of alternators is not a constant, and for the majority of purposes it is reasonable to assume a value of about 25 %. For a sudden short-circuit directly at the alternator terminals. the sub-transient reactance is about 20 %.

I see no objection to the terminals of an alternator being arranged at the side, although I agree with Mr. Kidd that from the point of view of the layout of the foundations it is preferable for the terminals to be at one end. I am also of the opinion that the lead extensions from alternator terminals have been responsible for the formation of ozone and that it can be eliminated by correct design. It is also good practice to insulate the lead extensions, and in view of the experience at Salt River it is now customary to enclose these leads in a compartment separated from the alternator air ducts.

The efficiency of an alternator at low loads is determined mainly by the windage, friction and iron losses, and there is no appreciable difference between a high-voltage and a low-voltage design.

I agree that for neutral resistors of the liquid type a horizontal plate is a relatively poor heat-dissipator, and that electrodes in the form of vertical cylinders are to be preferred. I do not think that the material is of importance if the current density is not excessive. The high-voltage (concentric conductor) alternator is equally as suitable as a low-voltage design for operation under the conditions mentioned by Mr. Kidd.

Short-circuit tests under the conditions mentioned by Mr. Bell would not be severe. Sudden short-circuit tests at full voltage are often specified and are applied directly across the terminals of high-voltage alternators.

In reply to Mr. Carr, my experience is that high-voltage concentric-conductor alternators generate less ozone than some low-voltage machines. I have referred to lead extensions and earthing resistors in my reply to Mr. Kidd. I agree with Mr. Carr that the earthing of a system should be considered on its merits.

Replying to Mr. Sammons the phenomenon of neutral inversion is not determined by the characteristics of the machine. The soundness of the joints is confirmed by the long and satisfactory experience with concentric-conductor alternators. The improvements mentioned in the paper have further increased their reliability.

I would refer Mr. Sutcliffe to my reply to Mr. Spence on the subject of the arrangement of the voltage transformers. The first consideration is the maintenance of the principle of phase separation; one of its most important advantages is that only faults to earth can occur. The fault current is limited by the earthing resistor, and can be interrupted very easily without the danger of a more severe interphase fault developing.

The earthing resistor should be designed to suit the system protective-gear and layout. If the fault current is limited to the full-load value at normal phase voltage the fault current at a remote point in the system may be much less. The fault current at any point must be sufficient to operate the appropriate protective apparatus.

The question of surge voltages is dealt with in my replies to Dr. Kahn and Mr. Kuyser. The distribution of capacitance in the concentric-conductor type of winding gives it inherent protection against voltage surges; no special means of protection are necessary, and none is provided for the majority of concentric-conductor alternators in service.

The list of single-conductor-type high-voltage alternators (Table A) supplied by Mr. Kilner is interesting, and his experience with the generation of ozone confirms the views I expressed in the paper.

For a direct comparison to be made between 11-kV and 33-kV alternators it is necessary that they should have similar design characteristics, the same type of winding and be similar in constructional details. While a number of tests have been made on high-voltage machines, it is difficult to meet these conditions. A comparison of the relative efficiencies of high- and low-voltage designs may be obtained from an examination of the major losses. With rotors of similar dimensions there should be no difference in the windage and the friction losses, and as the total losses are nearly equal the amounts of power absorbed by the fans should also be the same. The stator conductors of the high-voltage alternator occupy a little more space than those of the low-voltage alternator, and the volume of the teeth is greater. On the other hand, in the high-voltage machine the average tooth density is less and the iron loss in the teeth is approximately the same. In a similar manner the losses in the back of the core can be kept equal. With similar designs there is little difference in the rotor copper-losses, while the stator copper-losses are slightly reduced in the high-voltage alternator.

The stray-load losses in high-voltage alternators are of the same order as those in corresponding types of low-voltage winding. Owing to the small section of the conductors the eddy-current losses are reduced, while on account of the favourable distribution of the stator slots the rotor pole-face losses are less. Other losses are approximately equal. The total losses are slightly less in the high-voltage alternator, and it is thus more efficient than the corresponding low-voltage design, the increase being of the order of 0·1 %. It is estimated that the efficiency of a 66-kV alternator would be very little less than that of a machine wound for 33 kV, assuming that the design characteristics and other features are similar. Mr. Kilner's suggestion to insert a small reactor in the alternator neutral in conjunction with a resistor, to reduce harmonic circulating currents, should be effective.

In reply to Mr. Mellonie, the disadvantage of opening the neutral connection to interrupt a fault is that in some circumstances the fault may not be cleared, with the result that the potential in the other lines is raised to 73 % above normal to earth, and more faults may occur.

The relative dispositions of reactance in the high-voltage alternator and in the low-voltage alternator with transformer, is not likely to have a large effect upon stability, although theory and experience indicate that the former has a slight advantage.